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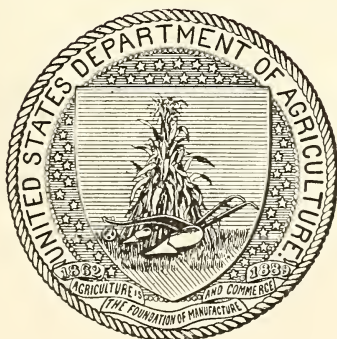
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MILTON WHITNEY, Chief.

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# INVESTIGATIONS IN SOIL FERTILITY.

BY  
MILTON WHITNEY

MILTON WHITNEY and F. K. CAMERON.



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## LETTER OF TRANSMITTAL.

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U. S. DEPARTMENT OF AGRICULTURE,  
BUREAU OF SOILS,

*Washington, D. C., September 15, 1904.*

SIR: I have the honor to transmit herewith a report on an investigation of the fertility of soils.

It can be readily seen from the nature of this report that it is essentially a report of progress in a line of investigation which will necessarily occupy our thought and energy for some time. I recommend that this report be published as Bulletin No. 23 of the Bureau of Soils.

Respectfully,

MILTON WHITNEY,  
*Chief of Bureau.*

Hon. JAMES WILSON,  
*Secretary of Agriculture.*

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# INVESTIGATIONS IN SOIL FERTILITY.

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## INTRODUCTION.

In a broad sense a fertile soil has been taken to mean one which usually produces a large crop. The yield would thus be a measure of fertility. The yield, however, is dependent not only upon the condition and properties of the soil, but upon the climatic conditions as well.

In a more restricted sense some agricultural investigators have endeavored to approximate the fertility of soils from the results of chemical analyses, recognizing that the yield of crops is not a measure of fertility, as the yield is dependent upon the kind of crops adapted to a particular soil, upon the texture of the soil itself, present mechanical conditions, drainage conditions, suitable climatic conditions, and efficient methods of cultivation. It is in a similarly restricted sense that the term will be used in this bulletin; that is to say, fertility is the inherent power of a soil to produce and support a satisfactory crop under favorable climatic conditions and suitable cultivation. To what this inherent power may be due, whether to definite amounts of plant food or to other causes, need not be more specifically stated at this point. Using fertility in this restricted sense, the conditions of climate, drainage, and cultivation, being more or less incidental and variable, would affect the yield but not necessarily the fertility of a soil.

In the course of this bulletin the words "good soils" and "poor soils" will be used. These expressions are intended in a relative sense, and are applied to soils of the same origin and texture and usually from adjoining fields, where they are under approximately the same climatic conditions but where under different treatment, either past or present, they have come to yield very different quantities of crops.

The terms "plant-food constituents" and "plant food" will be used with distinct meanings, the former relating to potassium, phosphoric acid, calcium, etc.; the latter either to combinations of these various constituents or to the particular constituents which are of themselves sufficient and proper food for the actual support of plant life. While a plant-food constituent may be in itself a food for plants it is not necessarily so.

The term optimum is used here to indicate the amount of water in a soil which would be most favorable to the development of a crop. What constitutes this optimum amount is somewhat arbitrarily determined, as a matter of judgment and experience.

The work described in the first part of this bulletin deals only with the movement of water in soils, which movement might be a factor in the fertility of soils. It does not consider the water capacity or the actual amount of water contained in soils, which has an enormous influence upon the yield of crops without necessarily affecting the fertility as above defined.

### THE MOVEMENT OF WATER IN SOILS.

A large number of investigations have been made on the relation of soils to the movement of water, but most of these have been confined to percolation experiments or to the capillary rise of water through dry or moist soils from a reservoir below. These conditions necessarily maintain the soil in a state of saturation, or, at least, at or near the optimum water content for plant growth. As a matter of fact, it is of minor importance to the agriculturist, except from the point of view of drainage work, to know how rapidly water moves through a saturated soil, or to what height water will ascend by capillary movement, as the water table in good arable soils should always be below 4 feet, and is usually as much as 25 or 50 feet below the surface, so that the conditions of the experiments mentioned are seldom encountered in the field. Furthermore, it is not the movement of water in a soil containing the optimum, but in a soil approaching the drought limit, that is of importance to this investigation. It is not the supply of water from which a plant can draw during a rainy spell, but the supply it can use during periods of dry weather, when the soils are taxed to furnish sufficient water to the plant, that would be expected to show the individual characteristics of the soils.

### EVAPORATION FROM MOIST SOILS IN CLOTH SACKS.

Samples were taken, 500 grams each, of Sassafras sandy loam, Sassafras loam, Norfolk sand, Cecil clay, and brick clay. The samples were passed through a mill to crush the lumps and to make the soil loose and pulverulent, but without actually crushing the individual mineral particles. The air-dry samples were then mixed with 14.5 per cent of moisture and put into cloth sacks, and hung in a basement room to evaporate at the ordinary temperature. The sacks were weighed frequently. The work was continued until about three-fourths of the moisture had been evaporated, when the final results showed that the Sassafras sandy loam had lost 42 grams of water, the Sassafras loam 50 grams, the Norfolk sand 54 grams, the Cecil clay 37 grams, and the brick clay 42 grams. It was thought at the time that the relative humidity of the basement room was rather high, and that the actual evaporation of water at the surface of the soils was so low that the capacity of the soils to transport water to the surface was not taxed—that is, that they were all capable, under the conditions of the experiment, of supplying water from the interior to the surface more

rapidly than it was removed by evaporation, and, in consequence, any difference due to the texture of the soils was not brought out.

Another experiment was tried by mixing about 500 grams of Sassafras sandy loam with different amounts of water, and, putting the dampened soil into the cloth sacks as before, allowing evaporation to proceed until about half the water had passed off. The results obtained from this experiment are given in the accompanying table.

*Loss of water by evaporation from 500 grams of Sassafras sandy loam mixed with different percentages of water and hung in cloth sacks.*

Water at beginning.		Weight of water lost.	Proportion of total water lost.
<i>Per cent.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>
4	20	10.6	53
6	30	15.8	53
8	40	20.1	50
10	50	23.0	46
12	60	25.1	42
14	70	26.7	38
16	80	24.2	30
18	90	24.4	27

Two objections to this method became apparent. In the first place, the evaporation was not entirely free where the samples were exposed, and it was believed the soils were not taxed to supply at the surface the loss due to evaporation under these conditions; and, in the second place, the handling of the sacks in obtaining the weights disturbed the condition of the soil more or less, and this was considered as possibly objectionable.

#### EVAPORATION FROM MOIST SOILS IN TIN CANS.

To meet these objections some tin cans,  $3\frac{1}{2}$  inches in diameter and about 2 inches high, were selected, filled level full with soil, and kept in the sun, as much as possible, and in a free circulation of air during the period of evaporation. These experiments were carried on during the months of August and September (1903), which happened to be unusually cool and often cloudy. The soils were in most cases mixed with water by hand, or in some cases with a spatula or with an egg beater before being put into the cans, to eliminate as far as possible any influence that might be induced through the method of mixing. Experiments were also made with cans filled with the dry soil, water being added carefully from the top and allowed to distribute itself under cover before the cans were exposed for evaporation. It may be stated, without going into details, that no notable differences were observed with any of these methods of procedure.

The following table shows the evaporation from ten types of soil of markedly different texture and agricultural value, when mixed with

water considerably short of the optimum quantity for good plant development:

*Evaporation of water from cans of different types of soil placed for several hours in the sun.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost.	Proportion of total water lost.
	Dry soil.	Water at beginning.			
	Grams.	Grams.	Per cent.	Grams.	Per cent.
Cecil clay .....	89.4	9.1	10	5.3	58
Yazoo clay .....	88.9	10.2	12	4.9	48
Hagerstown clay .....	82.5	6.3	8	3.8	60
Westphalia sand .....	88.3	3.2	4	1.5	47
Miami fine sand .....	80.2	4.2	5	2.5	60
Loess .....	75.1	4.5	6	2.6	58
Norfolk fine sandy loam .....	91.3	2.8	3	1.7	61
Sharkey clay .....	89.6	9.8	11	3.6	37
Windsor sand .....	90.9	3.1	3	2.2	71
Hagerstown loam .....	90.0	5.6	6	2.9	52

The Cecil clay, Yazoo clay, and Hagerstown clay are the strongest types of clay soil used for agricultural pursuits. The Sharkey clay is so heavy that it is in fact seldom used for agriculture, on account of the labor and expense attending its cultivation. On the other hand, the Windsor sand is so loose and porous that it is seldom cultivated.

The following table gives the evaporation from another set of samples, in 5-hour periods, for a total period of 25 hours. The soils at the beginning received approximately 15 per cent of water, and very nearly the same amount of water in the can, with the exception of the Norfolk sand, and the experiment was continued until the soils were nearly air-dry, or contained only about 4 or 5 per cent of water.

*Evaporation of water from cans of different types of soil, in 5-hour periods, for a total period of 25 hours.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost—					Weight of water remaining in the soil.	Proportion of water remaining in the soil.
	Dry soil.	Water at beginning.		During 5 hours.	During 10 hours.	During 15 hours.	During 20 hours.	During 25 hours.		
	Grams.	Grams.	Per ct.	Grams.	Grams.	Grams.	Grams.	Grams.	Grams.	Per ct.
Sassafras loam .....	339	44	12	7.2	17.8	24.4	30.7	37.1	7	2
Clarksville loam .....	278	42	15	6.2	14.6	19.8	25.4	32.0	10	4
Janesville loam .....	272	48	18	5.7	14.7	20.3	27.4	33.5	14	5
Ayden fine sandy loam .....	319	45	14	.....	24.7	38.4	44.8	44.7	0	0
Miami clay loam .....	278	46	17	6.5	14.5	19.8	25.5	32.1	14	5
Orangeburg sandy loam .....	346	47	13	9.2	31.3	44.7	51.1	51.3	.....	.....
Waverly silt loam .....	272	46	17	6.5	16.3	22.4	28.7	35.8	10	4
Susquehanna clay .....	354	44	12	6.8	17.0	23.3	30.1	37.6	8	2
Cecil clay .....	305	53	18	6.0	15.6	21.2	27.0	33.4	20	7
Norfolk sand .....	367	34	9	8.0	17.4	21.9	26.2	29.9	4	1



Evidence furnished by some of the experiments seemed to indicate that the evaporation from soils was approximately proportional to the amount of water the soil contained.<sup>1</sup> To investigate this point somewhat further, several types of soil were mixed with different percentages of water and put into cans as above, and subjected to evaporation. The quantities of water used were as nearly as possible 5, 10, 15, and 20 per cent, but the last only for the clay soils. The evaporation was carried on in an oven, at a temperature of 50° C., in a current of air. The results are given in the following table:

*Evaporation from soils to which different quantities of water have been added, to determine whether rate is proportional to the quantity of water.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost in 18 hours. <sup>a</sup>	Proportion of total water lost.
	Dry soil.	Water at beginning.			
	Grams.	Grams.	Per cent.	Grams.	Per cent.
Norfolk sand .....	{ 395.8	17.9	5	15.9	89
	{ 362.5	36.8	10	31.7	86
	{ 422.8	60.6	14	51.4	84
Cecil clay .....	{ 389	16	4	12.6	79
	{ 366.4	30.6	8	23.7	78
	{ 322.3	40.9	13	31.7	78
Hartford sandy loam .....	{ 326.9	64.1	20	55.3	86
	{ 409.3	22.1	5	17.6	80
	{ 412.4	46	11	36.3	80
Clarksville clay loam .....	{ 447.4	71.4	16	59.9	84
	{ 394.6	26.6	7	12.8	48
	{ 348.4	38.4	11	21.5	56
Windsor sand .....	{ 319.9	52	16	30.2	58
	{ 283.8	59.2	21	35	59
	{ 459.1	20.2	5	14.6	72
Loess .....	{ 468.6	42	9	31.6	75
	{ 500.1	56.6	11	45	80
	{ 361.6	19.2	5	12.4	65
Leonardtown loam .....	{ 352	34.8	10	19.1	55
	{ 283.2	41.6	15	27.7	67
	{ 415	79.1	19	48.8	62
Sassafras sandy loam .....	{ 390.3	17.3	4	10	58
	{ 367.4	31.1	9	16.1	52
	{ 352.7	49.3	14	25.6	52
	{ 387.3	19.8	5	10.4	53
	{ 347.4	34.7	10	18.8	54
	{ 348.4	60	17	39.6	66

<sup>a</sup> In three 6-hour periods.

Thirty different types of soil were selected from the collection in the Bureau, and the water content of the heavier soils brought up to approximately 17 per cent, and of the lighter soils to about 10 per cent.

<sup>1</sup> Widdtsoe and his colleagues (Bul. No. 80, Experiment Station of the Agricultural College of Utah, 1902, p. 101) have given expression to the fact brought out here and in some of the experiments described in the following pages in the form of a law: "The rate of loss of water from soils varies directly with the initial per cent of moisture in the soil."

The results with these soils are given in the table following.

*Evaporation from thirty different types of soil contained in tin cans exposed to the sun and wind for six hours.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost in 6 hours.	Water left in soil.	Proportion of total water lost.
	Dry soil.	Water at beginning.				
	Grams.	Grams.	Per cent.	Grams.	Per cent.	Per cent.
Sandhill .....	437.05	44.15	10	14.35	7	33
Windsor sand.....	440.58	43.62	10	18.60	6	42
Miami sand.....	406.89	41.91	10	13.55	7	32
Norfolk sand.....	388.23	40.82	11	14.85	7	36
Westphalia sand.....	303.29	35.19	12	8.05	9	23
Elsinboro fine sand.....	328.37	33.88	10	10.00	7	29
Miami fine sand.....	382.89	42.56	11	11.90	8	28
Norfolk sandy soil.....	436.39	43.21	10	20.60	5	48
Goldsboro compact sandy loam.....	366.63	37.82	10	13.10	7	35
Cecil sandy loam.....	425.74	43.91	10	9.05	8	21
Orangeburg sandy loam.....	374.70	38.75	10	11.40	7	29
Sassafras sandy loam.....	314.60	51.25	16	9.95	13	20
Ayden fine sandy loam.....	335.20	43.96	13	9.65	10	22
Norfolk fine sandy loam.....	326.50	60.44	18	8.55	16	14
Lake Charles fine sandy loam.....	306.60	51.81	17	8.15	14	15
Memphis silt loam.....	306.30	49.92	16	10.05	13	20
Clarksville silt loam.....	286.00	46.63	16	10.15	13	21
Waverly silt loam.....	276.50	50.61	18	8.55	15	17
Leonardtown loam.....	313.10	48.56	16	14.00	11	30
Sassafras loam.....	346.40	58.54	17	14.20	13	24
Hagerstown loam.....	298.40	46.60	16	9.85	12	21
Janesville loam.....	274.60	47.10	17	7.65	14	16
Miami clay loam.....	282.30	54.49	19	8.80	16	16
Miami black clay loam.....	284.00	80.16	28	7.45	26	9
Clarksville clay loam.....	288.60	48.78	17	10.35	13	21
Cecil clay.....	303.60	51.62	17	7.45	15	14
Hagerstown clay.....	303.40	48.56	16	9.70	13	19
Susquehanna clay.....	351.10	56.13	16	8.95	14	16
Yazoo clay.....	303.96	60.44	20	8.55	17	14
Sharkey clay.....	306.60	58.31	19	7.80	17	13

The samples are arranged in the table in about the order of their clay content, as shown by mechanical analysis.

The following table gives the results of still another experiment to determine if the loss by evaporation is directly proportional to the original water content of the soil:

*Evaporation from Sassafras sandy loam with different water contents.*

Proportion of water added.	Weight of—									Proportion of total water lost.
	Dry soil.	Water at beginning.	Water lost in 2-hour periods.						Water lost.	
			First period.	Second period.	Third period.	Fourth period.	Fifth period.	Sixth period.		
<i>Per cent.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>
5	379.80	19.00	1.05	0.85	1.05	0.45	1.15	0.60	5.15	27
7	349.60	23.45	1.25	1.05	1.40	.70	1.80	.70	6.90	29
9	330.70	28.80	1.65	1.40	1.75	.90	3.10	.90	9.70	34
11	325.15	34.20	2.00	1.75	1.95	1.05	2.00	1.10	9.85	29
13	315.30	39.40	2.25	2.00	2.40	1.35	2.75	1.25	12.00	30
15	316.15	46.15	2.70	2.70	3.05	1.75	1.85	1.40	13.45	29
16	379.80	60.85	2.00	6.55	8.65	7.55	4.35	.....	29.10	48
18	349.70	62.90	2.05	6.55	8.70	8.65	5.30	.....	31.25	50
20	330.75	66.15	2.05	6.90	9.20	9.55	6.15	.....	33.85	51
22	325.30	71.60	1.95	6.85	9.20	9.45	6.30	.....	33.75	47
24	315.30	75.70	1.95	6.80	9.35	9.35	7.35	.....	34.80	46
26	322.80	83.90	2.05	6.95	9.80	10.00	10.40	.....	39.25	47

The table is arranged in two groups. The samples with 5 to 15 per cent of water were weighed in 2-hour periods on July 24, while the samples containing 16 to 26 per cent were run on July 28, when the conditions of evaporation were very different, so that the total loss of water in these two periods can not be directly compared.

The following table gives similar data from three types of soil exposed to the sun:

*Evaporation from three types of soil, with different water content, in the sun.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost in 9 hours.	Water left in soil.	Water lost from soil.	Proportion of total water lost.
	Dry soil.	Water at beginning.					
	Grams.	Grams.	Per cent.	Grams.	Per cent.	Per cent.	Per cent.
Cecil clay .....	308.0	19.7	6	4.3	5	1	22
	296.7	27.9	9	6.0	7	2	22
	305.5	46.4	15	11.8	11	4	26
	310.2	56.1	18	7.7	16	2	14
	263.4	59.6	23	9.5	19	4	16
	228.1	62.6	27	13.0	22	5	21
Loess .....	318.6	20.7	6	5.5	5	2	27
	312.7	33.2	11	7.8	8	3	24
	311.8	42.5	14	8.3	11	3	20
	345.0	63.2	18	17.5	13	5	28
	408.8	91.2	22	19.0	18	4	21
	429.8	16.9	4	4.9	3	1	29
Norfolk sand .....	387.5	23.6	6	7.3	4	2	31
	401.4	33.0	8	11.4	5	3	35
	414.9	42.4	10	17.0	6	4	40
	452.9	54.9	12	25.5	7	5	46

After this exposure to the sun the same samples were put into a well-ventilated chamber, with a current of air forced through it, and kept for  $5\frac{1}{2}$  hours at a temperature of about  $50^{\circ}$  C., the results being given in the following table:

*Evaporation from three types of soil, with different water content, in an oven.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost in $5\frac{1}{2}$ hours.	Water left in soil.	Water lost from soil.	Proportion of total water lost.
	Dry soil.	Water at beginning.					
	Grams.	Grams.	Per cent.	Grams.	Per cent.	Per cent.	Per cent.
Cecil clay .....	308.0	15.4	5	3.2	4	1	21
	296.7	21.9	7	4.1	6	1	19
	305.5	34.6	11	4.5	10	1	13
	310.2	48.4	17	5.0	15	2	10
	263.4	50.1	20	7.6	17	3	15
	228.1	49.6	22	10.0	17	5	20
Loess .....	318.6	15.2	5	3.2	4	1	21
	312.7	25.4	8	4.5	7	1	18
	311.8	34.2	11	6.0	9	2	18
	345.0	45.7	13	10.0	11	2	22
	408.8	72.2	18	16.5	14	4	23
	429.8	12.0	3	2.2	2	1	18
Norfolk sand .....	387.5	16.3	4	3.2	3	1	20
	401.4	21.6	6	5.2	5	1	24
	414.9	25.4	6	6.8	5	1	27
	452.9	29.4	7	7.5	5	2	26



An experiment was then made to see if the compactness of the soil had an influence on the evaporation. The results of this experiment are given in the following table:

*Rate of evaporation from different types of soil under different conditions of compactness.*

Soil.	Weight of—		Proportion of water at beginning.	Water remaining in soil—				Water lost during entire period.	Proportion of total water lost.
	Dry soil.	Water at beginning.		At end of 6 hours.	At end of 12 hours.	At end of 18 hours.	At end of 24 hours.		
Cecil clay:	<i>Grams.</i>	<i>Grams.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>
Loose.....	284.45	66.85	24	21	19	17	15	9	37
Compact.....	393.95	92.60	24	21	19	17	14	9	40
Clarksville clay loam:									
Loose.....	256.60	31.30	12	11	10	9	7	5	41
Compact.....	403.85	49.25	12	11	10	9	8	4	34
Miami stony loam:									
Loose.....	288.75	39.00	14	12	11	9	8	6	42
Compact.....	462.30	62.40	14	12	11	9	8	5	39
Hartford sandy loam:									
Loose.....	342.00	23.95	7	6	5	4	3	4	58
Compact.....	526.50	36.85	7	5	4	3	3	4	63
Windsor sand:									
Loose.....	391.80	17.65	5	4	3	2	2	3	60
Compact.....	554.50	25.00	5	4	3	3	2	2	49
Podunk fine sandy loam:									
Loose.....	295.80	14.50	5	4	3	2	2	3	67
Compact.....	471.00	23.00	5	4	3	3	2	3	59
Norfolk sand:									
Loose.....	305.30	16.50	5	4	4	3	2	3	58
Compact.....	490.10	26.50	5	5	4	3	3	3	48
Loess:									
Loose.....	287.50	23.70	8	7	6	5	4	4	48
Compact.....	479.50	39.85	8	7	7	6	5	3	40

In this case the soils were mixed with water and put into cans in a loose condition on the one hand, and in a compact condition on the other, after which they were placed in the sun and ordinary currents of air to evaporate.

The following table shows the results of a similar experiment with three types of soil in which the degree of compactness was made even more pronounced than in the preceding experiment:

*Evaporation of water from different types of soil under different conditions as regards compactness.*

Soil.	Weight of—		Proportion of water at beginning.	Weight of water lost	Proportion of total water lost.
	Dry soil.	Water at beginning.			
	Grams.	Grams.	Per cent.	Grams.	Per cent.
Cecil clay.....	215.9	62.8	29	14.6	23
	293.9	85.4	29	18.5	22
	386.7	112.5	29	27.6	25
Hagerstown loam .....	216.2	29.4	14	8.5	29
	348.7	47.4	14	10.7	22
	443.6	60.3	14	17.0	28
Fort Meade tobacco soil.....	227.8	20.3	9	10.0	49
	389.8	34.7	9	14.1	40
	495.0	44.0	9	20.8	47

An experiment was then made with eight types of soil, of markedly different physical properties, by mixing them with from 10 to 15 per cent of water, subjecting them to successive periods of evaporation in an oven at a temperature of about 50° C., and in a strong current of air to insure perfectly uniform ventilation, and every night returning to the soil an amount of water equal to that lost by evaporation during the day. The purpose of this experiment was to see whether, by this continual wetting and drying and consequent change of structure of the soil, the amount of water lost during the different periods would be changed. It was found that the evaporation during the successive periods was approximately constant.

An attempt was then made to see if there could be brought about in some other way a change in structure which would influence materially the evaporation from the soil. For this purpose the Cecil sandy loam was mixed with different substances likely to have a marked effect upon the structure, such as ammonia, lime, and manure.

These cans were weighed at intervals of two or three hours, the results being given in the following table:

*Evaporation of water from Cecil sandy loam, with uniform initial water content and mixed with different substances likely to have a marked effect upon the structure of the soil and, presumably, upon evaporation.*

Period of evaporation.	Water evaporated from soil treated with—						
	Water alone.	Ammonia water.	Lime.	Manure.	Manure water.	Lime and manure water.	Dry manure mixed with dry soil. <sup>a</sup>
Hours.	Grams.	Grams.	Grams.	Grams.	Grams.	Grams.	Grams.
2½.....	0.8	0.6	0.7	0.4	0.6	0.9	1.0
5.....	1.8	1.6	1.8	.7	1.5	1.5	2.2
7.....	2.2	2.0	2.2	.8	1.8	1.8	2.8
9.....	2.4	2.3	2.5	.9	2.2	2.0	3.3
11.....	3.0	2.8	3.0	1.0	2.6	2.2	3.8
13.....	3.5	3.3	3.6	1.3	3.0	2.5	4.2
15.....	3.8	3.7	3.8	1.4	3.4	2.7	4.4
17.....	4.0	4.0	4.1	1.5	3.6	3.0	4.7
19.....	4.2	4.2	4.3	1.6	3.8	3.2	5.0

<sup>a</sup> The water added subsequently to the mixing of the manure with the soil.

Certain experiments in which small glass tubes and ordinary tumblers were used, when placed upon a hot plate, or upon a stone surface in the sun, showed the peculiar phenomenon of an excessive loss of water from below—that is to say, a change of color was frequently noticed on the bottom, or on the side exposed to the sun, which indicated a more rapid drying in that part than in other parts of the soil mass. It was suspected, therefore, that evaporation, which had been used as the measure of the transporting power of a soil, did not take place at the surface alone, but throughout the soil to a considerable depth, and that the presumption upon which the foregoing experiments were undertaken, i. e., that the water moved through capillary or similar agencies to or near the surface before evaporation, was untenable.

To determine this point definitely, a sample of Cecil clay containing 12.26 per cent of moisture, which is below the optimum for plant growth, was placed in a tumbler with cheese cloth above it, leaving a quarter of an inch air space immediately over the moist soil. The actual weight of soil used was 223.85 grams, containing 27.4 grams of water. On the cheese cloth, immediately over the soil and completely covering the top of the tumbler, was placed a layer of air-dry Cecil clay about 1 inch thick, and weighing 55 grams. The tumbler was put into a well-ventilated oven at a temperature of about 50° C., and in ten days the moist soil had lost 19.9 grams, or 73 per cent of the total amount of water originally present. A more careful determina-

tion was made in the same way with some Cecil clay subsoil, with the results contained in the following table:

*Evaporation from Cecil clay subsoil placed in tumblers and covered with air-dry soil 1 inch deep, with one-fourth inch air space between, and placed in an oven with strong ventilation for three days.*

Proportion of water at beginning.	Weight of—			Proportion of total water lost.
	Water at beginning.	Dry soil.	Water lost.	
<i>Per cent.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>
20	53.2	267.0	25.5	48
24	58.3	239.4	29.1	50
33	80.5	243.6	47.2	59
33	79.3	240.1	45.7	58

Another experiment was made by putting 100 grams of water in each of three tumblers, with an inch in depth of Cecil clay in one case, and of Leonardtown loam in another, supported over the water on cheese cloth, leaving the third without covering, as a check. The loss through evaporation is shown in the table appended:

*Evaporation from water confined below a layer of dry soil.*

Soil layer over the water.	Weight of—				
	Water at beginning.	Water lost during 4 hours in oven.	Water lost during night.	Water lost during 4 hours in oven.	Total water lost.
	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>
Cecil clay.....	100	4.7	0.75	3.5	8.95
Leonardtown loam.....	100	8.6	2.25	5.0	15.85
None .....	93	.....	.....	18.6	18.6

The tumblers as prepared were allowed to evaporate for 4 hours in a well-ventilated oven at 50° C., when the water under the Cecil clay had lost 4.7 grams and that under the Leonardtown loam 8.6 grams. Overnight at room temperature the loss was respectively 0.75 and 2.25 grams. The next day, in 4 hours in the oven, the water under the Cecil clay lost 3.5 grams and that under the Leonardtown loam 5 grams, and water in a similar tumbler without a soil covering lost 18.6 grams, or a little over three times as much as that under the Leonardtown loam and a little over five times as much as that under the Cecil clay. The total loss under the Cecil clay was somewhat less than half as much as that under the Leonardtown loam, showing apparently a marked influence in the resistance offered by these two soils to the passage of water vapor.

Lastly, experiments were made by Mr. Mooney, of this Bureau, at Statesville, N. C., by carefully pressing brass cylinders, 3 inches in

diameter and 3 inches high, into the soil of a field of Cecil clay, after removing the top 3 inches of soil, digging these cylinders out carefully, covering the bottom with a thin rubber dam to prevent evaporation, and permitting the samples to evaporate in the sun and air. The results are contained in the following table:

*Loss of water by evaporation from Cecil clay soil taken from field in brass cylinders and exposed to sun and air.*

Grade of soil.	Weight of—		Proportion of water at beginning.	Weight of water lost after drying 8 hours.	Proportion of total water lost.
	Dry soil.	Water at beginning.			
	Grams.	Grams.	Per cent.	Grams.	Per cent.
Good to medium.....	397.3	73.9	19	18.6	25
	421.1	59.8	14	11.6	19
	340.3	50.4	15	8.2	16
	326.6	49.6	15	8.5	17
	407.3	46.8	12	6.8	14
	394	45.7	12	7.2	16
	429.1	49.8	12	7.6	15
	Average.....	387.9	53.7	14	9.8
Medium to poor.....	371.4	49.7	13	8.4	17
	421.2	57.7	14	9.2	16
	361	45.1	13	7.7	17
	422.1	32.5	8	5.4	17
	460.7	56.6	12	12.6	22
	400	46.4	12	8.1	17
	430.6	48.2	11	5.3	11
	351.5	61.5	18	9.5	15
Average.....	402.3	49.7	12	8.2	16

These samples were collected from fields of different degrees of productiveness, as indicated by the condition of crops growing upon them. The first part of the table gives the results from soils classed as good to medium; the second part the results from soils ranging from medium to poor. The extremes in the yield of crops from soils thus studied may be placed at 25 bushels of wheat per acre for the best soils and from 3 to 5 bushels of wheat per acre for the poorest soils. Similar experiments were made by Mr. Taylor on good and poor Leonardtown loam, at Leonardtown, Md., with similar results.

To study this matter of evaporation from soils somewhat more fully, some tin cylinders were made, 2, 4, 6, and 8 inches in depth, respectively, with closed bottoms, in which soil was placed and allowed to evaporate in the sun and air.



The following table gives the results of such an experiment with Cecil clay containing 17.15 per cent of moisture in each of the cylinders:

*Loss by evaporation from Cecil clay containing 17.15 per cent of moisture, exposed to the sun and air in cylinders of different depths.*

Length of cylinder.	Weight of—			Proportion of total water lost.
	Dry soil.	Water at beginning.	Water lost.	
<i>Inches.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>
2	224.28	38.5	27.9	73
4	472.04	81	28.9	36
6	738.11	126.6	27.7	22
8	980.37	168.1	29	17

When the 2-inch cylinder had lost about 73 per cent of its water the actual loss of water in grams from each of the four cylinders was about the same. After this experiment was completed, moisture determinations were made in each half-inch layer in each of the cylinders, with the results contained in the following table:

*Water in each half-inch layer of soil in each of the cylinders at close of preceding experiment.*

Depth.	2-inch cylinder.	4-inch cylinder.	6-inch cylinder.	8-inch cylinder.
<i>Inches.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>
0.5	4	5	5	6
1.0	5	7	10	6
1.5	6	11	11	9
2.0	7	13	14	12
2.5	.....	15	15	13
3.0	.....	14	16	14
3.5	.....	16	17	15
4.0	.....	15	17	16
4.5	.....	.....	17	16
5.0	.....	.....	17	17
5.5	.....	.....	17	17
6.0	.....	.....	17	17
7.0	.....	.....	.....	17
8.0	.....	.....	.....	17

It is clearly apparent that, while the soils had lost the same amount of water in grams, the deeper cylinder had lost water from at least 4 or 5 inches. These cylinders were allowed to rest in the sun on a stone window frame which became heated to a considerable extent, and it was apparent that there was slightly more evaporation in the bottom than in the layers immediately above, although naturally not so much in this case as from the top layers of the soil. The results given in the foregoing table are shown diagrammatically in figure 1.

In another experiment several cans were filled with Cecil clay, mixed with 15.7 per cent of water, and put into a well-ventilated oven

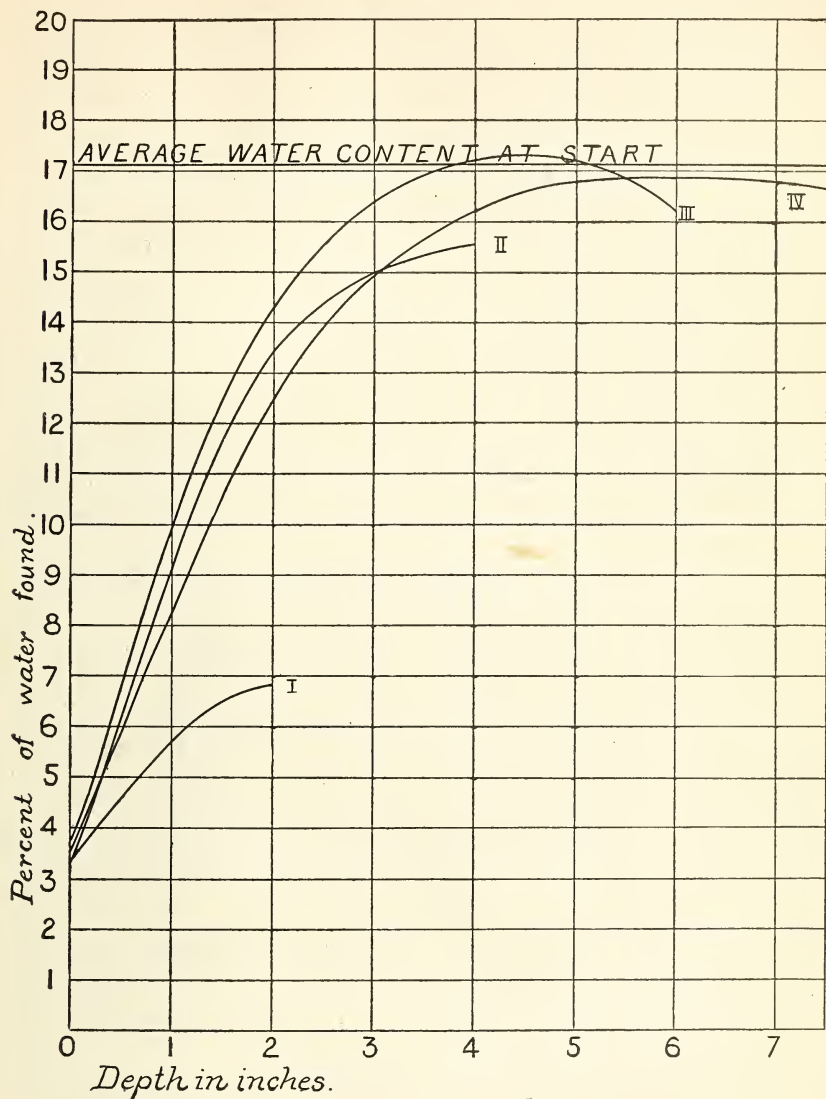


FIG. 1.—Distribution of water in Cecil clay subsoil, in cans of different depths, after evaporating for twelve days in open air. Initial water content, 17.15 per cent. Moisture determinations made for each half inch of depth. I, 2-inch can; II, 4-inch can; III, 6-inch can; IV, 8-inch can.

at 50° C. These were taken out at intervals of two hours and the contents divided into five equal parts from the top downward.

The quantity of moisture in each of these depths is shown in the following table:

*Water in various depths of Cecil clay originally containing 15.7 per cent of water, after evaporation for different periods of time in tin cans 2 inches deep in a well-ventilated oven at 50° C.*

Time of drying.	Weight of—		Proportion of water at beginning.	Water remaining in soil.				
	Dry soil.	Water at beginning.		First layer.	Second layer.	Third layer.	Fourth layer.	Fifth layer.
Hours.	Grams.	Grams.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
2	352	54	16	9	12	13	14	14
4	346	54	16	7	11	12	12	12
6	364	57	16	4	8	9	10	10
8	348	54	16	2	6	8	9	9
10	356	55	16	2	5	8	8	9
12	363	57	16	1	4	6	6	5
16	354	55	16	1	2	5	6	4
18	381	52	16	0	1	2	4	5

Figure 2 shows the moisture determinations as above in five different layers in cans of soils that have been allowed to evaporate for from 2

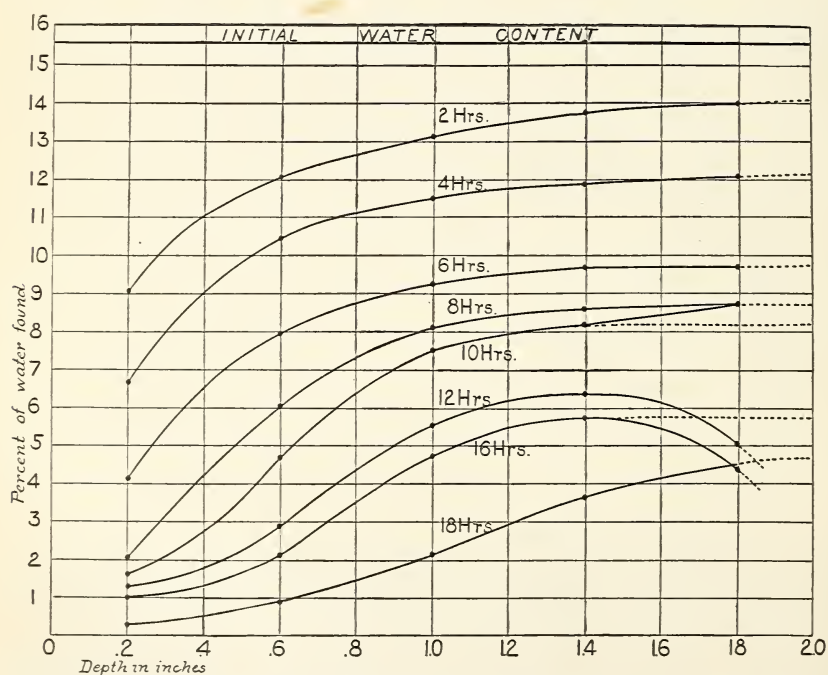


FIG. 2.—Distribution of water in good Cecil clay, in cans 2 inches deep, after evaporating for different periods in a well-ventilated oven at about 50° C.

to 18 hours, the eight cans being opened and moisture determinations made in the different layers immediately after removal from the oven.



That this effect is mainly due to evaporation and not to the movement of water to the surface is indicated in figures 3 and 4, based upon determinations in which some of the cans were opened immediately after being taken out of the oven, and others were left closed for from 20 to 41 hours to prevent evaporation, and to see to what extent a uniform distribution of the water in the soil would be reestablished. The shape of the curves shows very clearly the actual disturbance of

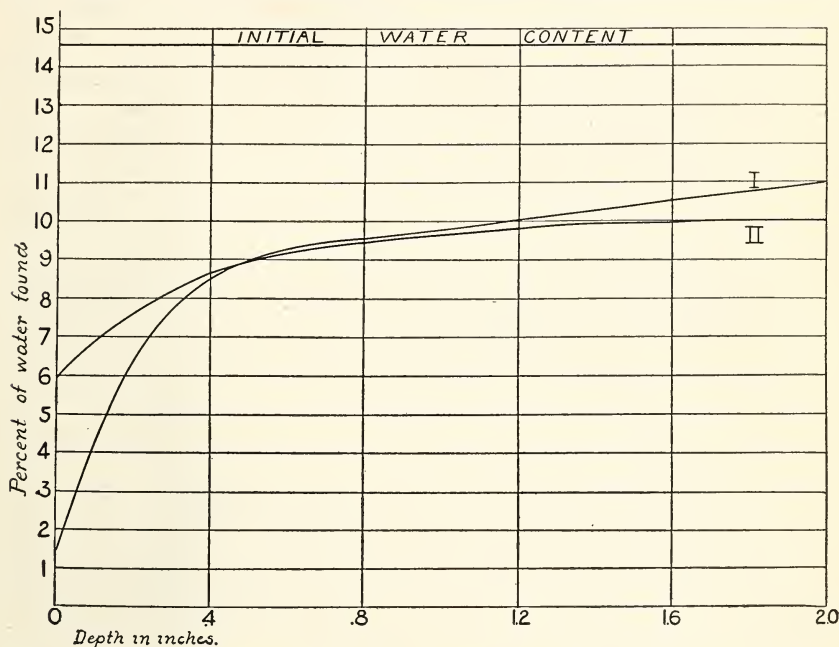


FIG. 3.—Redistribution of water in good Cecil clay, in cans 2 inches deep, after disturbance by evaporation for six hours in a well-ventilated oven at about 50° C. Initial water content, 14.55 per cent. I, Distribution immediately after removal from oven; II, distribution twenty hours later, after standing covered, at room temperature.

the water distribution in the soils by the evaporation and the extent to which a restoration toward uniform distribution has taken place on standing.

#### MOVEMENT OF WATER IN SOILS SHORT OF SATURATION.

When it was found that the loss due to evaporation was not alone a surface phenomenon, but, on the contrary, that a large part of this loss of moisture was due to evaporation within the soil itself, and when it became evident that evaporation could not be used as a measure of capillary movement of water, a different line of experiments was taken up. An effort was made to disturb the equal distribution of the water within a soil by a short period of evaporation, and then to enable the water to redistribute itself uniformly by letting the soil remain for a

period protected against evaporation, but the difficulties of determining accurately just how much the distribution had been disturbed by the evaporation, and to what extent it had been restored to uniformity, were so great as to make this method unsatisfactory.

In all this work the difficulties attending accurate determinations of the moisture in the soil will be appreciated by those who have had these matters to deal with, and the errors in such determinations are relatively so large that slight differences in the soil moisture can not readily be stated with accuracy, except by establishing an average through a large number of determinations. The following method was finally employed for determining the movement of water between soils of different water content, and has given fairly satisfactory

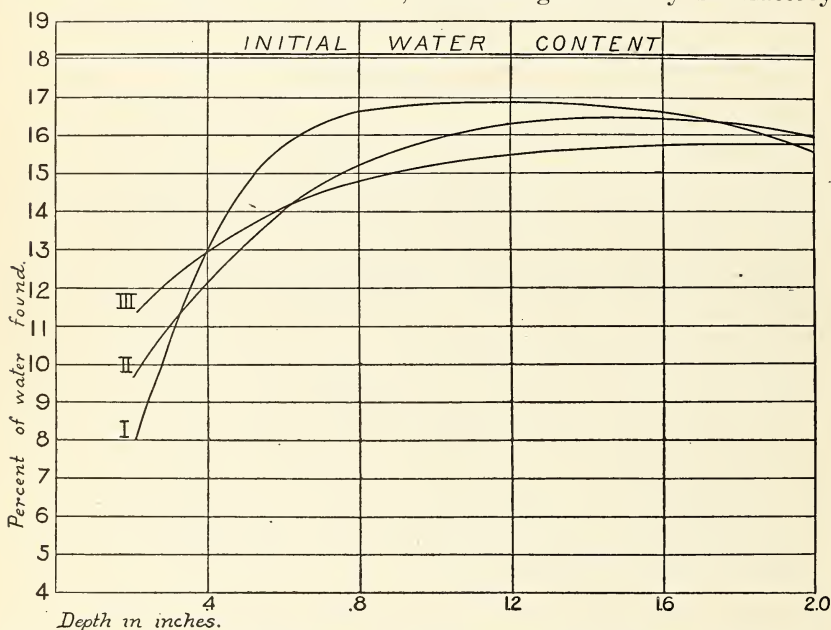


FIG. 4.—Redistribution of water in Cecil clay subsoil, in cans 2 inches deep, after disturbance by evaporation for six hours in a well-ventilated oven at about 50° C. Initial water content, 18.2 per cent. I, Distribution immediately after removal from oven; II, distribution after standing seventeen hours, covered, at room temperature, since removing from oven; III, distribution after standing forty-one hours, covered, at room temperature, since removing from oven.

results. Glass tubes about 1 inch in diameter and  $3\frac{3}{4}$  inches long, and closed at one end, which could be protected at the top with ordinary cork stoppers, were at first used, but later ordinary glass tumblers covered with rubber dams were found to answer very well, and had the advantage that a larger volume of soil could be used. The rubber dam, stretched tightly over the top and secured readily by rubber bands, prevented evaporation.

With either the tubes or the tumblers air-dry soil, for which moisture

determinations had been made, was used. Enough soil mixed with an amount of water sufficient for the optimum conditions for plant growth was taken to half fill the tumbler. Generally speaking, this optimum was about 8 per cent for sandy soils, 12 to 15 per cent for the lighter clays and loams, and 20 to 25 per cent for some of the heavier clays. In all cases the soils were thoroughly worked up with the water until they were in what would be considered excellent tilth. This moist soil was carefully placed in the tumbler or tube and compacted by slight jarring, or, in some cases, by compressing it with a wooden pestle. On top of this was placed an equal weight of soil, either in the air-dry state or with any given moisture content below the optimum with which it was desired to experiment. This was compacted in the same way as the moist soil, and the tumbler or tube covered so as to prevent evaporation altogether, and allowed to remain for a certain time for the moisture to adjust itself.

It was at first supposed that the drier soil should have some moisture in it over and above the quantity normally present in its air-dry condition, for it was believed that the movement of water would be different in an air-dry soil and in a slightly moist soil.

It was found, however, that the capillary movement of water from a wet into an air-dry soil follows precisely the same laws, and is of about the same relative magnitude, as the movement from a wet soil into a drier soil, but one more moist than in hygroscopic equilibrium. It was thus possible, instead of putting a soil with 5 or 10 per cent of water on top of the moist soil, to use air-dry soil and get equally satisfactory results, and as this procedure was generally easier air-dry soil was frequently used.

For the purpose of experiment, soils were selected of markedly different agricultural values. A sample of Cecil clay from Statesville, in fine condition, yielding annually from 20 to 25 bushels of wheat, and a sample of the same soil from an adjoining field under poor cultivation and classed unquestionably as a poor soil as measured by its productivity, with reported yields of from 3 to 5 bushels per acre; samples of a good and a poor Leonardtown loam from St. Mary County, Md.; a sample from a lawn at Takoma Park, D. C., which is exceedingly poor, practically no vegetation being found upon it; one from a bed at Takoma Park made in this lawn by heavy applications of manure; one from a sod at Takoma Park upon which comparatively large yields of grass are annually produced; from a crab-grass plot at Takoma Park; from a meadow or pasture, and from a brick or tile clay deposit at Lamond Station, D. C., were the soils that were chiefly used.

The table on the next page gives the results of some experiments in which soils with different moisture content were put together and allowed to remain for from 2 to 24 hours.

*Movement of water in soils short of saturation.*

Soil.	Water before contact—		Time of contact.	Water after contact, in top layer.
	In top layer.	In bottom layer.		
	<i>Per cent.</i>	<i>Per cent.</i>	<i>Hours.</i>	<i>Per cent.</i>
Cecil clay:				
Good .....	11	21	2	12
Do .....	11	21	2	12
Good subsoil .....	13	22	12	13
Poor .....	12	23	2	13
Do .....	19	30	2	20
Poor subsoil .....	14	24	2	15
Do .....	14	24	2	16
Leonardtown loam:				
Good .....	12	23	2	14
Do .....	12	23	2	14
Poor .....	10	20	2	11
Do .....	7	14	2	8
Do .....	7	14	2	7
Lawn at Takoma, poor .....	5	15	12	8
Do .....	5	15	12	7
Do .....	5	15	12	7
Do .....	8	15	24	8
Do .....	8	15	24	9
Do .....	8	15	24	8
Do .....	8	15	20	8
Do .....	8	15	20	9
Do .....	8	15	20	8
Bed at Takoma, heavily manured .....	6	16	12	9
Do .....	6	16	12	7
Do .....	6	16	12	7
Do .....	11	17	24	10
Do .....	11	17	24	10
Do .....	11	17	24	10
Do .....	6	11	12	8
Do .....	6	16	12	8
Do .....	6	21	12	10
Do .....	10	17	20	10
Do .....	10	17	20	10
Do .....	10	17	20	10
Department grounds .....	11	21	6	12
Do .....	11	21	6	12
Do .....	11	21	6	12
Crab-grass plot at Takoma .....	8	16	24	9
Do .....	8	16	24	9
Do .....	8	16	24	9
Do .....	8	16	20	9
Do .....	8	16	20	9
Do .....	8	16	20	9
Pasture at Takoma .....	12	22	12	13
Sod at Takoma, good .....	13	22	12	15
Brick clay .....	13	23	12	14
Do .....	14	23	12	16
Do .....	14	23	12	16
Clover soil, Brightwood .....	9	16	12	10



A uniform distribution of the water has in no case been completely established, and on the average only about 25 per cent of the possible movement appears to have taken place. With these experiments, and particularly in others which are to follow, where air-dry soil was placed in contact with soil containing an optimum amount of water, it was apparent that the water did not become uniformly distributed through the drier layer, but on the contrary it moved up in such a way that the lower portion of the drier layer in contact with the moist soil at once approached the optimum. Thus while the movement during the first few hours, amounting as above indicated to about 25 per cent of the possible movement, was rapid, it did not extend to any considerable depth of soil, but appeared to be confined largely to a narrow layer adjacent to the wet soil. At the end of the experiment it was frequently possible to pour off the loose dry soil down to within a quarter of an inch of the wet soil, below which the material was so moist that it had to be removed with a knife or other similar instrument. Even where soils have been allowed to remain in contact for a month, and evaporation has been prevented, the surface layers appeared and in fact were shown by moisture determinations to be little if any more moist than at the beginning of the experiment.

The following table shows the movement in a tile clay from Lamond Station, D. C., with different percentages of moisture in the bottom layer of soil, and a uniform amount in the top layer:

*Movement of water in a tile clay short of saturation.*

Water before contact.		Time of contact.	Water after contact, top.
In top layer.	In bottom layer.		
<i>Per cent.</i>	<i>Per cent.</i>	<i>Hours.</i>	<i>Per cent.</i>
4	24	12	8
4	19	12	6
4	14	12	5
4	9	12	5

A sample of purified quartz sand, mixed with 4 per cent of water, was placed in the bottom of a tube, and on this was placed an equal weight of dry sand. At the end of 12 hours the top half contained 0.25 per cent of moisture and the bottom half 3.1 per cent. The difference in the moisture content at the end of the period was still quite distinguishable to the eye in the difference in color on the side of the glass. A sample of quartz flour was prepared with 18.5 per cent of water in the bottom and 9.3 per cent in the top. This was left for 12 hours, after which the top was found to contain 10.7 per cent, or an increase of 1.4 per cent, and the bottom 15 per cent, or a decrease of 3.5 per cent.

The following table gives the results of an experiment with Cecil clay containing 15 per cent of moisture with an equal amount of air-dry soil on top. In this case the tubes were opened at intervals, the first in 2 hours and the last in 72 hours.

*Movement of water in Cecil clay soil short of saturation.*

Water before contact—		Time of contact.	Water after contact, in top layer.
In top layer.	In bottom layer.		
	<i>Per cent.</i>	<i>Hours.</i>	<i>Per cent.</i>
Air-dry .....	15	2	2
Do .....	15	12	3
Do .....	15	24	5
Do .....	15	48	5
Do .....	15	72	6

The following table gives the results of an experiment where different amounts of air-dry soil were placed in contact with a soil containing 20 per cent of water:

*Movement of water in Cecil clay soil short of saturation and with different amounts of air-dry soil in contact with the moist soil.*

No. of tube.	Position in tube.	Weight of soil used.	Water before contact.	Water after contact.
		<i>Grams.</i>	<i>Per cent.</i>	<i>Per cent.</i>
1	{Top.....	30	Air-dry.	6
	{Bottom.....	30	20	16
2	{Top.....	30	Air-dry.	7
	{Bottom.....	30	20	15
3	{Top.....	10	Air-dry.	13
	{Bottom.....	30	20	17
4	{Top.....	10	Air-dry.	13
	{Bottom.....	30	20	18

The fact that brings out more clearly than anything else the difference in the movement of water in a soil when containing an optimum amount and when in a drier condition, is the behavior of water when it is poured onto the surface and allowed to percolate into the soil. If air-dry soil is packed into a tumbler and an amount of water equal to the optimum water content be poured onto the surface, it percolates quite rapidly, and in a few hours a uniform distribution is established. If, however, considerably less than the optimum quantity be added, the water percolates into the soil for only a short distance, and uniform distribution is not established in intervals of time measured by weeks and months. That is to say, if the soil contains in its optimum 15 per cent of moisture, 15 cc. of water will diffuse through 100 grams of soil quite readily if the water is applied rapidly to the surface, but if only  $7\frac{1}{2}$  cc. of water is applied it will not distribute itself uniformly through the soil.

The following table shows the results of placing together soils of the same kind, with the optimum and 20 per cent less than the optimum water content, in the bottom and top layers, respectively, and leaving them in contact for from 2 to 168 hours:

*Experiment to determine the extent and rate of movement of water from soil at optimum water content to soil at less than optimum.*

Soil.	Weight of—		Proportion of water before contact.	Proportion of water in soil after contact for—						Average.
	Soil.	Water.		2 hours.	4 hours.	24 hours.	48 hours.	96 hours.	168 hours.	
Cecil clay (water mixed with soil):	<i>Grams.</i>	<i>Grams.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>
Top .....	27	4.70	16	16	16	17	17	17	16	16
Bottom .....	27	5.83	21	21	19	21	20	20	21	20
Top .....	27	4.70	16	16	16	16	17	16	16	16
Bottom .....	27	5.83	21	21	20	20	20	21	20	20
Hartford sandy loam (water mixed with soil):										
Top .....	25	1.18	5	6	6	6	.....	a 5	b 4	5
Bottom .....	25	1.56	6	7	6	6	.....	a 6	b 5	6
Top .....	25	1.18	5	5	5	5	.....	a 5	b 5	6
Bottom .....	25	1.56	6	7	8	6	.....	a 5	b 6	6
Top .....	25	1.56	6	6	5	5	.....	a 5	b 5	5
Bottom .....	25	1.18	5	5	.....	5	.....	a 5	b 5	5
Hartford sandy loam (water added to soil):										
Top .....	26	1.40	5	.....	.....	6	6	.....	.....	6
Bottom .....	26	1.75	7	.....	.....	6	6	.....	.....	6
Top .....	26	1.40	5	.....	.....	6	6	.....	.....	6
Bottom .....	26	1.75	7	.....	.....	6	6	.....	.....	6
Top .....	26	1.90	7	.....	.....	7	6	.....	.....	7
Bottom .....	26	1.55	6	.....	.....	6	6	.....	.....	6

a For 72 hours.

b For 144 hours.

In the effort to determine whether in the movement of water in soils short of saturation there were differences that could be related in any way to the yield of crops, a large number of experiments were made. The following will serve to indicate their general character:

*Movement of water in soils of different moisture content, standing in contact in closed tube for one month.*

Soil.	Water before contact—		Water after 30 days' contact—		Proportion of possible movement.
	In top layer.	In bottom layer.	In top layer.	In bottom layer.	
Cecil clay:		<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>
Good .....	Air-dry ..	20	8	13	78
Poor .....	.....do ..	20	10	14	83
Good .....	.....do ..	10	5	7	83
Poor .....	.....do ..	10	6	9	84
Good .....	.....do ..	5	3	4	88

In this case tubes of good and poor Cecil clay were prepared with 5, 10, and 20 per cent of water in the bottom layer and air-dry soil above, and the two layers were allowed to remain in contact for thirty days.

Another set of samples was prepared in the same way in tumblers, and opened at intervals of a few days during a period of about a month. The results are given in the following table:

*Movement of water in soils of different moisture content, short of saturation, standing in contact for different periods of time.*

Soil.	Water before contact—		Weight of water in top soil after contact for—				Proportion of possible movement in—			
	In top layer.	In bottom layer.	4 days.	7 days.	14 days.	28 days.	4 days.	7 days.	14 days.	28 days.
Cecil clay:	<i>Per ct.</i>	<i>Per ct.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>	<i>Per ct.</i>
Fertile .....	1	16	6.1	6.7	6.8	5.9	55	71	72	76
Poor .....	3	18	6.8	7.9	7.9	7.2	61	70	70	83
Leonardtown loam:										
Fertile .....	1	16	4.2	5.0	5.6	5.2	45	52	60	71
Poor .....	1	16	4.3	5.4	5.5	5.1	49	60	61	72
Lawn at Takoma, very poor .....	1	16	3.9	4.5	5.0	4.6	46	56	57	66
Bed at Takoma, well manured.....	1	16	4.1	5.0	5.1	4.1	45	52	53	65

In order to study this in even greater detail, a set of tubes was prepared with productive Cecil clay soil, its subsoil, and Norfolk sand, one of the tubes being taken down each day and moisture determinations made.

*Movement of water in soils short of saturation.*

Number of days in contact.	Proportion of possible movement between layers of—			Number of days in contact.	Proportion of possible movement between layers of—		
	Cecil clay soil (good), containing at beginning 2.14 per cent of water in top and 15.32 per cent in bottom layer.	Cecil clay subsoil, containing 0.08 per cent water in top and 18.60 per cent in bottom layer.	Norfolk sand, containing 0.75 per cent water in top and 8.75 per cent in bottom layer.		Cecil clay soil (good), containing at beginning 2.14 per cent of water in top and 15.32 per cent in bottom layer.	Cecil clay subsoil, containing 0.08 per cent water in top and 18.60 per cent in bottom layer.	Norfolk sand, containing 0.75 per cent water in top and 8.75 per cent in bottom layer.
	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>		<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>
1 .....		37	31	18 .....	74	85	
2 .....	53		44	19 .....	73	84	59
3 .....	58	58	46	20 .....		86	53
4 .....	61	61	46	21 .....		88	48
5 .....	64	71	51	22 .....		73	
6 .....	70	74		23 .....			
7 .....	76	73	48	24 .....		86	
8 .....		76	55	25 .....		88	
9 .....	70		54	26 .....		90	
10 .....	73	79	66	27 .....		88	60
11 .....	75	81	56	28 .....		80	
12 .....	77	80	54	29 .....		80	
13 .....	76	87		30 .....			
14 .....	67	78	59	31 .....		89	
15 .....		80	54	32 .....		87	
16 .....	74		54	33 .....		84	
17 .....	71	84	60				



A diagram (fig. 5) illustrating this last experiment will bring out the points that can not easily be seen in the text. The variation in the position of the points is just as likely to be due to unavoidable inaccu-

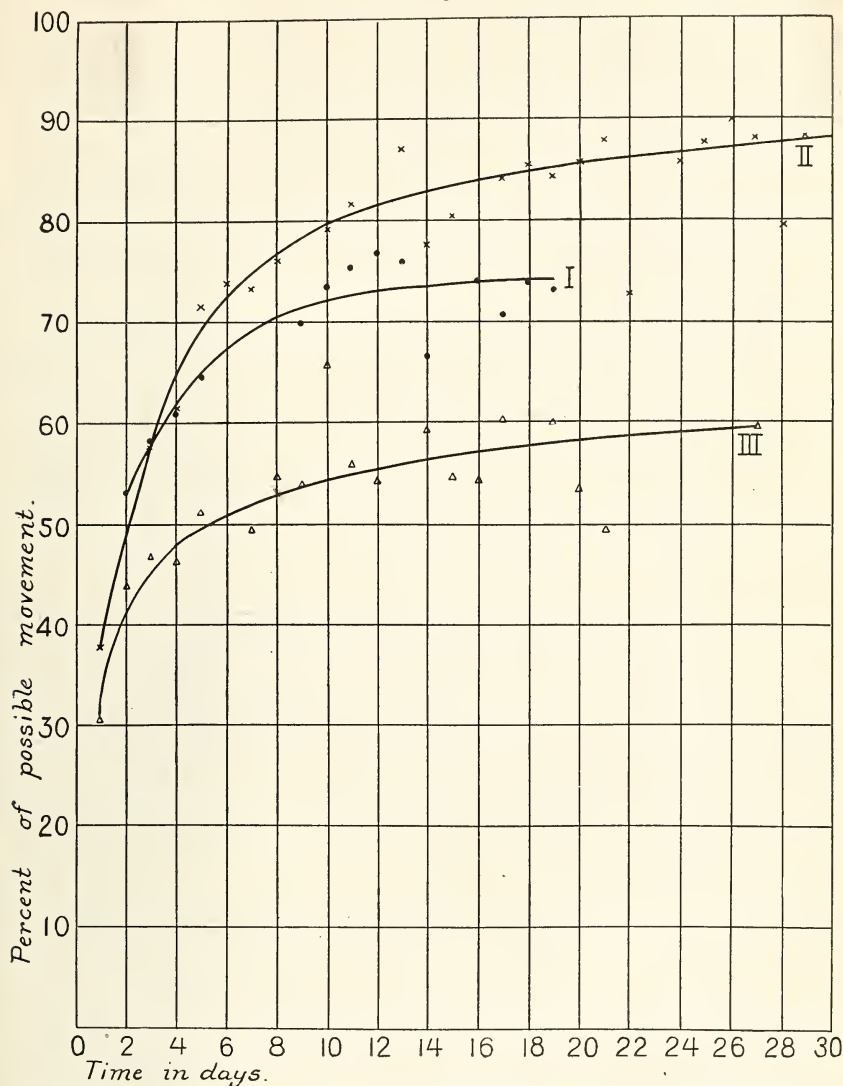


FIG. 5.—Movement of water between layers of the same soil of initially different water content. I, Cecil clay, fertile; II, Cecil clay subsoil; III, Norfolk sand.

racies in sampling and in the moisture determinations as to any real difference in the actual water content of the soil, although it is probable that all these factors have influenced the results.

# ABSORPTION OF WATER BY SEEDS FROM DIFFERENT TYPES OF SOILS.

No relation being established between the movement of water with its associated plant food and the fertility of soils, the next question which presented itself was whether the plant itself had difficulty in obtaining its water supply from the soil. The first method tried in investigating this subject was the absorption of water by seeds. For this purpose lima beans and lupines were chosen, being large seeds, easily handled, and readily freed from any adhering soil. These were put into soil contained in tumblers and allowed to remain for some time, when they were taken out, wiped off, and the increase in weight determined.

The following table gives the results of one of these experiments:

*Water absorbed by lima bean and white lupine seeds in contact with various soils for twelve hours.*

Soil.	Water added.	Kind of seed.	Number of seeds.	Weight at beginning.	Weight at end.	Proportion of water absorbed.
Leonardtown loam:	<i>Per cent.</i>			<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>
Good.....	15	{ Lima .....	6	6.05	9.70	60.3
		{ Lupine .....	12	5.25	8.10	54.3
Poor .....	15	{ Lima .....	6	6.30	9.90	57.1
		{ Lupine .....	12	4.75	7.60	60.0
Tile clay from Lamond Station....	15	{ Lima .....	6	5.70	6.65	16.7
		{ Lupine .....	12	4.85	5.55	14.4
Loam at Takoma, very poor .....	10	{ Lima .....	6	5.95	8.65	45.4
		{ Lupine .....	12	4.50	6.35	41.1
Flower bed at Takoma, well manured. }	10	{ Lima .....	6	5.75	8.05	40.0
		{ Lupine .....	12	4.70	6.30	34.0
White clay from Soldiers' Home, D. C. }	15	{ Lima .....	6	6.75	9.90	46.7
		{ Lupine .....	12	5.25	7.90	50.5
Cecil clay:						
Good .....	15	{ Lima .....	6	6.10	9.15	50.0
		{ Lupine .....	12	5.15	7.45	44.7
Poor .....	15	{ Lima .....	6	6.35	8.60	35.4
		{ Lupine .....	12	4.75	6.10	28.4

In the above experiment lupine and lima bean seeds were put into different types of soil, ranging from compact tile clay to good Cecil clay, and containing from 10 to 15 per cent of moisture. These were allowed to remain in contact with the soil for 12 hours.

The following table gives the results from different types of soil, where the seeds have been left in contact for different lengths of time:

*Water absorbed by lima beans from different soils in different lengths of time.*

Soil.	Water added.	Number of seeds.	Time of contact.	Weight at beginning.	Weight at end.	Gain.
	<i>Per cent.</i>		<i>Hours.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Per cent.</i>
Lawn at Takoma, very poor .....	12.5	5	6	7.15	8.20	14.7
		5	20	6.20	9.80	58.1
		5	44	6.25	12.00	92.0
Bed at Takoma, well manured .....		5	6	6.40	7.25	13.3
		5	20	6.05	9.20	52.1
		5	44	6.40	11.40	78.1
Cecil clay, fertile .....	12.6	5	6	6.50	7.55	16.2
		5	20	6.95	10.85	56.1
		5	44	5.85	11.05	88.8
Cecil clay, poor .....	21.0	5	6	5.70	6.65	16.6
		5	20	6.05	9.80	62.0
		5	44	6.20	11.50	85.4
Clover subsoil, Brightwood.....	11.4	4	6	4.90	5.65	15.3
		4	20	5.20	7.80	50.0
		4	44	5.00	8.25	65.0
Tile clay from Lamond Station.....	20.0	4	6	5.00	5.55	11.0
		4	20	4.55	5.95	30.8
		4	44	4.75	6.65	40.0

It will be observed that the amount of moisture absorbed increased with the length of time up to 44 hours, but still there is no evidence that the infertile soils supply less water to the seed than the more fertile ones. Lima beans require from 100 to 120 per cent of their dry weight of water to germinate, as was determined in another experiment, and the same experiment showed that they were able to obtain the requisite amount of water, under the conditions maintained, from fertile as well as from infertile soils, and from sand as well as from brick clay.

There was no observable difference in the amount of moisture absorbed by seeds in soils of the same water content, whether manure had previously been added to the soil or not. The power of seeds to absorb water from the soil is very great. Fifty grams of cowpeas mixed with 50 grams of soil containing 15 per cent of water, in 12 hours had themselves gained 12.1 per cent of water and left in the soil 1.3 per cent; that is, the soil was practically air-dry. Air-dry seeds contain on the average about 14 per cent of water. Air-dry soil contains on the average about 2 per cent of water. It is probable, therefore, that the power of seeds to absorb water is very much greater than that of soils, and that the seed with 14 per cent of water would be in equilibrium with about 2 per cent of water in the soils. Other experiments in the laboratory confirmed this.

Another interesting phenomenon observed is that small seeds like clover and wheat germinate if left on the surface of a moist soil, provided evaporation be prevented or the atmosphere above the seed be saturated with water vapor. Lima beans, however, when left upon the surface of the soil, with only one side of the seed in contact with the soil, can not absorb the necessary 100 per cent of their weight of water, and consequently fail to germinate, even if left in contact with the soil until they mold or rot. It is necessary in this case to have both sides of the seed in contact with the soil in order to insure germination.

An interesting fact was developed in connection with this. The movement of water from a moist to a dry soil usually takes place to a limited depth of the dry soil; that is to say, if the moist soil has an optimum water content, the water appears to move into the dry soil in a compact body, bringing the lower layer into nearly an optimum condition, and does not diffuse uniformly in the soil, as one would expect, through the contraction of the film of water throughout the whole mass of the drier soil. It has been roughly estimated that the influence of the drier soil on the moist soil is of such a magnitude that probably the larger portion of the water moving in a week is all contained within one-fourth inch of the dry soil next to the line of contact.

Other observations make it appear that the seed can draw water only from about one-fourth inch from its surface. Why this should be, is not apparent, but the fact is that the soil immediately around the seed often gets very dry and at times nearly air-dry, while one-eighth of an inch away, to judge by the color or general appearance of the material, little or no change in the water content takes place. It appears, therefore, that a small seed like that of clover or wheat can get sufficient moisture to ensure germination, even if but a single side is in contact with the soil, but that a large seed like the lima bean, requiring much more water, can only get sufficient water from one-fourth inch on all sides. It seems highly probable from the experiments made that if the lima bean were round instead of flat it could not get sufficient moisture from a soil unless the water supply were renewed by rain or otherwise at least once during the period of germination. With the form which the lima bean has, it would appear that if it required 160 per cent instead of 120 per cent, the seed could not germinate in a soil containing the optimum amount of water unless the supply were renewed by at least one rainfall or one watering during the period of germination.

It must be remembered in applying the results of the movement of water in soils to the case of plants which have germinated and possess root systems that the absorbing tip of the root is constantly moving into new regions, continuing its absorption at any one point for only a few hours, or at most but two or three days.

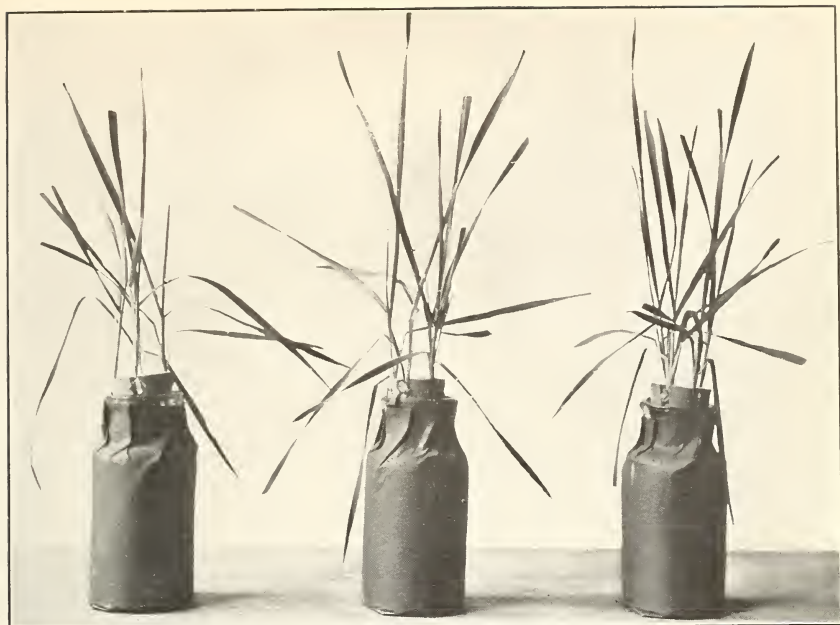


FIG. 1.—METHOD OF GROWING WHEAT SEEDLINGS IN SOLUTIONS.

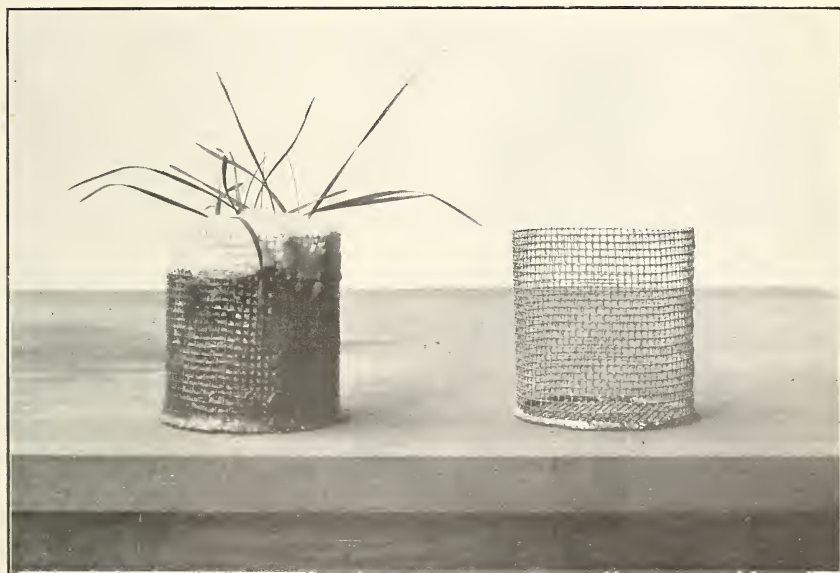


FIG. 2.—METHOD OF GROWING PLANTS IN SOILS CONTAINED IN WIRE BASKETS COVERED WITH PARAFFIN.







DEVELOPMENT OF WHEAT SEEDLINGS IN AQUEOUS EXTRACTS OF SOIL: 1, FROM POOR CECIL CLAY; 2, FROM GOOD CECIL CLAY; 3, FROM POOR LEONARDTOWN LOAM; 4, FROM GOOD LEONARDTOWN LOAM.





**EXPERIMENTS WITH CULTURE MEDIA.**

It will be shown in the following pages that the plant itself experiences more difficulty in obtaining its moisture, and with reasonable certainty the salts contained in that moisture, from some soils than from others, and that with the soils examined the difficulty is greater in those recognized as of low fertility than in soils which are recognized as fertile.

The fact that the availability of the moisture and its dissolved salts is due to something other than the texture or physical condition of the soil was shown by growing plants in an aqueous extract of the soil, when it was found that the plants showed the main characteristics of growth and development that were associated with them when grown in the soils themselves. This was noticed in a most marked way in the much less transpiration from plants growing in the extracts from poor soils, although there was no sign of wilting in any of these plants. It was also seen in the larger and more healthy development of the root systems of the plants growing in the extracts from the good soils, and lastly in the greater development and more healthy appearance of the leaves of the plants grown in the extracts from the good soils. The difference in the transpiration became apparent and continued for some time before there was any noticeable difference in the appearance of the root systems or in the character and amount of leaf surface. But invariably, when a sufficient length of time had elapsed, it was found that the greater amount of transpiration was associated with the greater development of root systems and of leaves. No accurate measurements were taken of either of these two parts of the plants, but the great differences observed in the transpiration precluded any possibility of this being due merely to an unequal increase in the root system or in the growth of the leaves of the plants, although associated with such unequal increase, for the differences in these latter respects were at first so small as even to escape the eye of careful observers.

The absolute magnitude of the transpiration from a seedling plant, within a short period of time and under favorable conditions, is so large as to render slight experimental errors in determining it of comparatively minor importance. It therefore appeared that a way was offered to compare soils or culture solutions by their effects upon the functional activities of plants under conditions susceptible of easy control.<sup>a</sup> In experiments already referred to, it was early observed

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<sup>a</sup>At first sight it would appear simpler and better to take the change in weight of the plant as the criterion of its development. It is practically impossible to satisfactorily separate a plant from adherent soil particles and moisture without injuring it, and in the case of soil culture, at least, repeated transplantings would be incompatible with a normal development of the plant. In some of the experiments in

that after the transpiration at different rates had persisted for several days, the root systems were developing differently, and the plants growing in the "good" solutions had the larger and more healthy looking root systems. It was realized that the greater transpiration from these plants might in part be due either to the larger system of roots, or to their healthier condition. To test this point, solutions were prepared from a good and a poor Cecil clay, respectively, and seedling wheat plants were grown in each for about a week, with daily exposure to the sunlight under as uniform conditions as the best care could obtain. The roots of the plants were immersed twice daily, or oftener, in fresh portions of the solutions drawn from large stock solutions.<sup>a</sup> At the end of this period there was observed a considerable difference in the transpiration from the plants in the two solutions; and the plants which had transpired the most had decidedly larger and healthier root systems, and a somewhat better development of leaves, although in this last respect the differences in the plants were not very marked. The plants were then changed, those which had been growing in the poor solution being immersed in the good, and vice versa. The effect was almost immediate and quite pronounced, and within a few

this investigation the plants were weighed at the end of the experiment, and while the figures obtained were small they were always in the same order as the transpiration figures. The magnitude of the transpiration figures, and especially the fact that they could be obtained at short intervals of time, thus giving a control over the experiments, made them appear especially well adapted to this line of work. See also in this connection Demoussy [Compt. rend., 127, 771 (1898)] who has used transpiration in a similar manner in studying the absorption of salts by plants.

<sup>a</sup> These stock solutions were made up in several portions and brought together. A part of the solutions in which the plants had been grown for from 12 to 24 hours was also saved. Partial analyses were made in several of these solutions, and the averages are given in the following table, the columns headed "Before" indicating that the solution had not been used for the plant, while those headed "After" indicate that plants had grown in the solution.

*Parts per million of solution.*

	NO <sub>3</sub> .		PO <sub>4</sub> .		K.		Ca.	
	Before.	After.	Before.	After.	Before.	After.	Before.	After.
Good .....	3.2	1.5	1.6	1.6	3.6	1.9	3.2	3.2
Poor.....	3.5	1.3	1.6	1.6	2.0	1.8	2.8	2.4

These figures indicate that there were no especial differences between the two solutions as regards amounts of mineral nutrients present, so far as they can be determined by analytical methods we now possess. Extracts from both good and poor soils possessed a neutral reaction. They were thoroughly aerated by pouring from one vessel to another before the plants were immersed in them. Owing to the somewhat indefinite way in which these solutions and figures obtained from them were assembled, no definite conclusions regarding the action of the plants upon them can be drawn.

days the plants growing in the good solution, though then possessing the smaller root systems, showed a higher rate of transpiration than the plants with the larger root systems but growing in the poor solution. Precisely similar results were obtained with aqueous extracts of a good and a poor Leonardtown loam, respectively. From these, as well as other experiments which have been made, it seems fair to conclude that the mere size of the root system, at least within wide limits, does not alone control the rate of transpiration from the plants, a conclusion which was confirmed by an examination of the literature of this subject. It was therefore clear that within the limits involved in this work it would be safe to regard the size of the root system as a negligible factor in the amount of transpiration, and that only the condition of the roots need be considered in this connection.<sup>a</sup>

Under the conditions of the experiments, therefore, as carried out in these investigations, it seemed justifiable to take the rate of transpiration as to some extent coincidental with and indicative of the condition and growth of the plant.

#### EXPERIMENTAL METHODS.

A simple method of determining the amount of transpiration was used. Seedling plants were grown in prepared solutions contained in 2-ounce bottles, each with a stopper having slits in the circumference, into which the plants were fitted, with some cork slips over them to hold them in place and to prevent direct evaporation from the inside of the bottle. The bottle was of black opaque glass and the plants were kept in the sun throughout the day. The bottles containing the plants were weighed daily, and the loss of weight taken as the measure of transpiration. Such precautions were taken that the amount evaporated directly from the bottle was so small that it could be ignored, while the daily amount transpired by the plants was from two to ten times the weight of the plant, and the increased growth of the plant from day to day during the period of the experiment is therefore taken as negligible for purposes of the experiments.

The seeds were germinated at first in ordinary moist blotting papers, which were of course carefully sterilized. But it was found that seedlings germinated in clean building or river sand were, for purposes of

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<sup>a</sup>It is not likely that the extent of the root system will influence in any marked degree the transpiration from the plant, provided the root system is sufficiently large and healthy to supply the plant at all times with an adequate amount of moisture. If, on the other hand, transpiration be excessive and the loss of water more than the roots can supply, wilting will occur, and finally the collapse and death of the cells. It was developed in the course of these investigations that when the plants showed a difference in transpiration the *relative* differences exhibited on damp, cloudy days was nearly the same (the total amount transpired being small) as on bright, clear days, when the transpiration was very large.



these experiments, in every respect as suitable as those germinated in blotters, and that the use of sand possessed a number of advantages. This method was used for obtaining nearly all the seedlings employed in the experiments here described. The sand was contained in small wooden trays and kept at the desired temperature for from six to eight days, when, usually, the seeds had germinated and, in the case of wheat, produced plumules about an inch in length, or of a suitable size to be transferred to culture solutions. A number of plants were tried, including wheat, corn, oats, lupine, cowpeas, clover, and mustard. For many reasons wheat seedlings were found the best adapted to this work, and it should be understood, unless specifically stated otherwise, that this plant was used. The method of mounting the seedlings is shown in Plate I, figure 1.

It was foreseen that the solubility of the glass bottles used might possibly have an effect on the plants, but the change in the electrical resistance of distilled water, when kept in the bottles for several days, indicated that such solubility effect could be neglected. This indication was further confirmed by interchanging bottles containing solutions in which plants were showing difference in transpiration, when no effects were detected which could be ascribed to the solubility of the glass.

In order to eliminate as far as possible all outside influences which might affect transpiration, small-sized bottles which could be readily shifted or arranged were used, and for each solution tested at least three, and often thirty, bottles, containing from 12 to 120 seedlings, were used for each test or duplicate. It seems altogether probable that such source of error was eliminated as might be due to individual variations in the plants.<sup>a</sup> The bottles were usually placed on light trays in a compact bunch, each series of experiments being kept together under identically the same conditions and the position of the bottles in the tray being frequently changed. From the appearance of the plants it would seem that the conditions of growth were very well maintained, in that perfectly normal and healthy plants were produced, except in unusually hot, humid summer weather, when the transpiration was small, in which case the development of fungus in the culture media was frequently observed, necessitating the abandonment of the experiments thus affected.

The investigations were made in culture solutions, or solutions made with chemically pure salts, and in soil extracts. A culture

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<sup>a</sup>It should be observed that these seedlings (in groups of twelve or more) were all carefully selected individuals chosen from a very large number (several hundred usually) for the express purpose of securing uniformity. It, therefore, seemed reasonable to expect that possible variations due to individual characteristics were for the most part eliminated by this selection, and that the number of seedlings in each group would be quite sufficient to eliminate any tendency to variation which might persist in the individuals after this selection.

solution was first made according to Wolff's<sup>a</sup> well-known formula. With a fuller knowledge and experience in handling these plants it was found possible to vary the constituents at will; so that shortly after the work was begun the conventional nutrient solution of Wolff was abandoned and a wide latitude was allowed in the preparation of the nutrient material.

In the case of the soil extracts the usual procedure was to digest 1,000 grams of soil with 1,250 cc. of distilled water, stir the mixture for 3 minutes and allow it to settle for 20 minutes. It was then filtered under pressure through a recently burned and washed Pasteur-Chamberland filter tube. With the filtering machine devised by Briggs<sup>b</sup> 2 liters of such an extract can be made in the course of 2 hours. It is perfectly clear and usually colorless and is presumably free at first from all organisms such as bacteria and molds. Care was exercised in all cases to have these solutions well aerated, and to this end they were frequently renewed, the fresh portion being poured back and forth rapidly from one vessel to another, drawn up in a pipette and then allowed to flow into the containing bottle in a narrow stream, beaten up into a foam with an egg beater, or air was blown through the solutions in small bubbles, the choice of these methods being determined by circumstances and the special conditions under which the particular experiments were performed.<sup>c</sup>

No attempts were made in this investigation to carry plants to maturity by growing them in culture solutions, since it was realized that this would involve very serious difficulties, and it was very doubtful whether strictly comparable conditions could always be maintained and controlled. But such control can be readily maintained over a period of five to six weeks, the extreme limit of growth which was found necessary or desirable in these researches.

Experiments were attempted, using glass tumblers, but were soon abandoned because of the difficulty of obtaining a good contact between the soil itself and the walls of the tumbler. The soil on being moistened usually contracted somewhat, leaving an air space surrounding it practically saturated with water vapor, and in this air space by far the greatest proportion of the plant roots were developed so that the inherent properties of the soil itself produced little or no effect upon the plant, since it was in contact with so little of the absorbent area of the root system. It was thought that this difficulty might be overcome by placing a glass tube in the center of the pot through which water and air might be carried to the bottom of the soil. But here

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<sup>a</sup>Johnson: *How Crops Grow*, p. 168 (1869).

<sup>b</sup>Bul. No. 19, p. 33, Bureau of Soils, U. S. Dept. Agr., 1902.

<sup>c</sup>It was recognized that in these aeration processes there was a great danger of inoculating the solutions with bacteria or fungus spores, and solutions which showed any sign of being thus affected were excluded.



again the roots were found at the end of a few days' growth to be almost entirely around the tube or against the walls of the tumblers and not in the soil itself. After numerous trials a form of retainer was devised which has proved eminently satisfactory.

A small cylindrical basket was made, 3 inches deep and 3 inches in diameter, of galvanized wire netting of  $\frac{1}{4}$ -inch mesh. These wire baskets received a thin coating of paraffin. The soil containing the desired percentage of moisture was put into the basket, without, however, quite filling it, the seedling plants being introduced in a single row. The sides of the basket were gone over with a brush or other convenient instrument to remove all surplus soil particles and the basket was then weighed. It was allowed to stand for several hours (usually twenty-four hours) until the soil had dried out somewhat and contracted. It was again weighed to determine the loss in moisture, after which it was again brushed, to remove all loose particles of soil, and immersed in a bath of very hot paraffin nearly to the surface of the soil, until bubbles of air began to come off, when it was quickly withdrawn. When this coat of paraffin had cooled slightly, the basket was dipped into some paraffin of a temperature just above the melting point, so as to fill up the spaces in the wire basket. This gave a perfect coating of paraffin, which was held in place by the wire, and a hardpan of cemented grains on the surface of the soil, which the roots could not penetrate. Paraffin was then put about the upper part of the wire basket where it extended above the soil, thus providing a convenient cup for adding water to the soil. Finally, a light sand was put on the surface to protect the soil from wash, the basket again weighed, and water added to bring the soil up to the optimum water content. In order to check evaporation directly from the soil, after the plants had been growing some days, circular sheets of paper with narrow slits cut in them were paraffined, fitted around the plants, and securely fastened to the pots by paraffin around the outer edges in such a way as to slope toward the plants. A wad of cotton was then tucked closely about the plants on each side to prevent evaporation through the slits.

This form of basket (Pl. I, fig. 2) has been eminently satisfactory, and the plants growing in the contained soils have shown the same order of differences in transpiration as were shown by plants growing in the extracts from the same soils. A number of these baskets have been taken apart and the root system examined. In no case has there been found any evidence of any effort on the part of the roots to develop toward the sides of the pot. On the contrary, they grow freely throughout the soil. It was found desirable, when wheat seedlings were used, to plant but six in each of these wire baskets, spacing them as uniformly as possible, and at the end of the experiments the soil was always carefully removed and the condition of the roots carefully observed.

The baskets were weighed daily, and the loss in weight taken as a measure of the amount of water transpired by the plants. After each weighing an amount of distilled water equal to that lost during the preceding day was carefully added, in order to maintain the water content of the soil at the optimum. At the conclusion of the experiments, an inspection of the soils showed a uniform distribution of water in the soils.

#### EXPERIMENTS WITH SOIL EXTRACTS.

In one case 16 wheat plants in a period extending from October 2 to 30, inclusive, gave a total transpiration of 277.1 grams in the Cecil clay, good; and 171.7 grams in the Cecil clay, poor.

In a second case the same number of wheat plants, from October 5 to 28, inclusive, in experiments carried on at a different place, gave a total transpiration of 141.50 grams from the extract of the good Cecil clay and 97 grams from the poor Cecil clay.

In a third experiment 12 wheat plants, from November 1 to 18, inclusive, gave a total transpiration of 115.80 grams from the extract from the good Cecil clay and 103.9 grams from the extract from the poor Cecil clay.

Experiments of the same kind with 16 wheat plants, from October 30 to November 20, gave a total transpiration of 193.45 grams from an extract of good Leonardtown loam and 135.70 grams from an extract of poor Leonardtown loam.

Similar work was carried on in extracts from a very poor lawn at Takoma Park, D. C., and from a fertile sod at the same place. From October 30 to November 20 the total transpiration from the lawn extract was 90.05 grams and from the sod 152.35 grams. In both cases 16 wheat seedlings were used. The diagram (fig. 6) on page 40 shows the daily transpirations in these two soils.

#### EXPERIMENTS WITH SOILS IN BASKETS.

While these experiments with soil extracts offered quite an easy method for investigating the relative fertility of soils, it was realized that this method alone did not furnish sufficient criteria unless supported by similar results from plants grown in soils. Experiments were therefore made to determine the transpiration from plants grown in wire baskets.

Sixteen wheat plants thus grown, from November 23 to December 22, gave a total transpiration from good Cecil clay of 246.55 grams and from poor Cecil clay 193.10 grams.

At the termination of the experiment the tops of the plants were cut off and weighed, the soil was removed from the basket, and, after being weighed, subsamples were taken out for moisture determination. The volume of the soil was determined by filling the basket with water to

where the surface of the soil had been and weighing this. From these data the amount of air space was calculated, assuming the specific gravity of the soil to be 2.65. The following observations were made: The soil was found to be in very good tilth, with a somewhat granular structure, and although the total amount of water which had been transpired was several times greater than the amount originally present, the daily losses having been replaced, the soil was uniformly moist throughout its entire depth. The roots were well distributed through the soil, showing no tendency to segregate either to the side or to the bottom of the

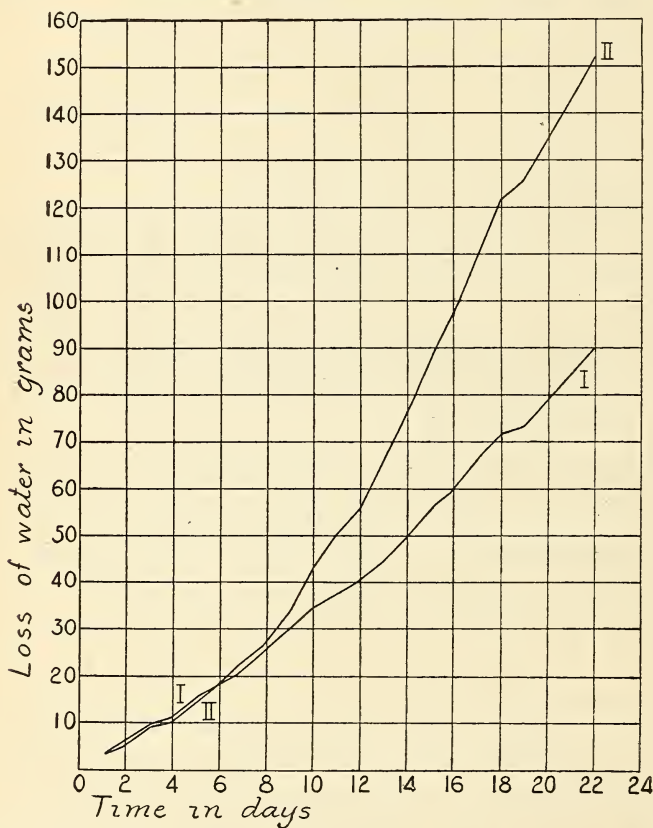
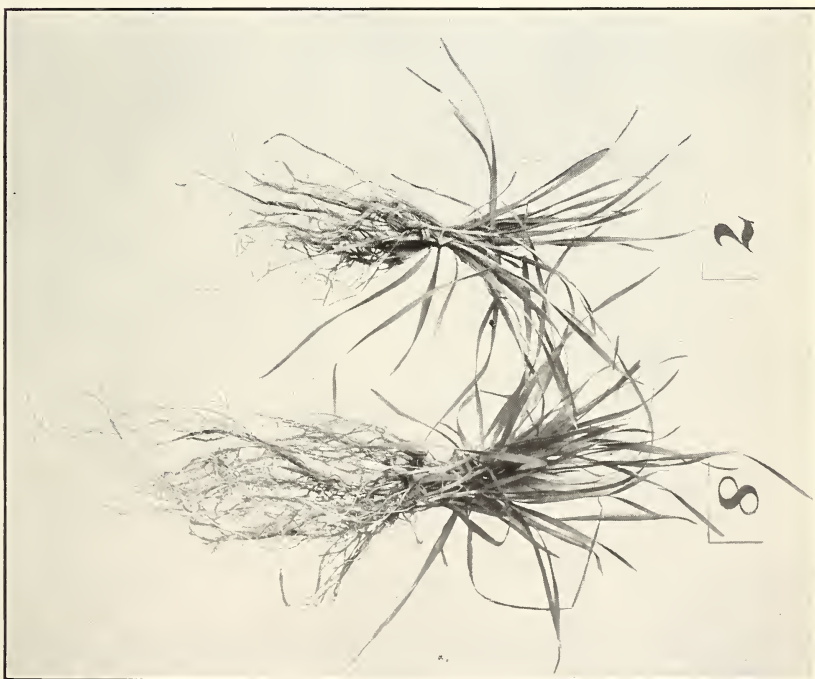


FIG. 6.—Total quantity of water transpired by 16 wheat plants growing in aqueous extracts of a lawn and a sod soil from Takoma Park, D. C. I, Lawn, very poor; II, sod, good.

basket. The following figures are averages for each of the three baskets, and refer in each case to six plants, the number grown in one basket. The plants on the Cecil clay, good, weighed 0.45 gram, fresh weight, while the six plants from the Cecil clay, poor, weighed 0.31 gram. The superficial volume of the soil was 276.38 cc. and 274.50 cc., respectively. The weight of dry soil was 363.45 grams in the first case and 279.55 grams in the second. The weight of water present was 56.32 grams or 15.46 per cent in the Cecil clay, good, and 74.17 grams or 26.51



DEVELOPMENT OF WHEAT SEEDLINGS IN AQUEOUS EXTRACTS OF SOIL: 5, FROM POOR LAWN, TAKOMA PARK, D. C.; 6, FROM GOOD SOD, TAKOMA PARK, D. C.; 7, FROM POOR CECIL CLAY, STATESVILLE, N. C.; 8, FROM POOR CECIL CLAY, MANURED, STATESVILLE, N. C.







DEVELOPMENT OF WHEAT SEEDLINGS IN AQUEOUS EXTRACTS OF SOIL: 9, FROM GOOD CECIL CLAY; 10, FROM GOOD CECIL CLAY, MANURED.



per cent in the Cecil clay, poor, both being at their optimum. The volume of air space in the soil was 82.93 cc., or 30.02 per cent of the entire volume of the Cecil clay, good, and 94.84 cc., or 34.73 per cent of the volume of the Cecil clay, poor. The root systems of the plants in the Cecil clay, good, were considerably larger, better developed, more branched, and had a better appearance than those in the Cecil clay,

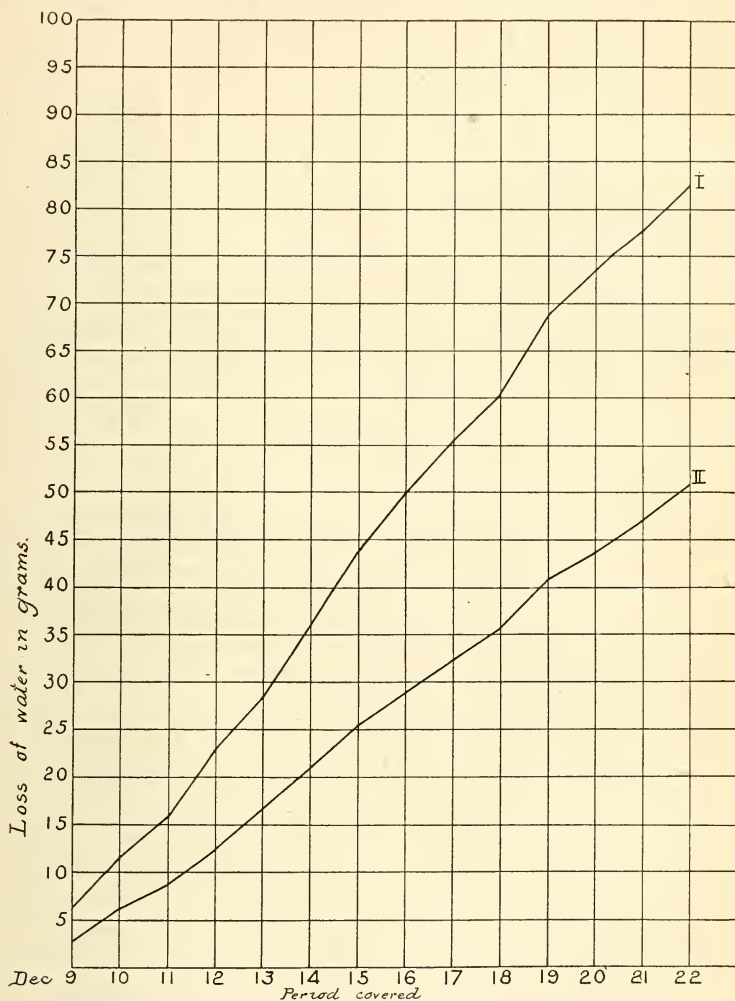


FIG. 7.—Total quantity of water transpired by 18 wheat plants growing in good and in poor Cecil clay in wire baskets. I, Good Cecil clay; II, poor Cecil clay.

poor. Fig. 7 shows diagrammatically the transpiration from these plants for the last two weeks of the experiment.

Experiments of the same kind were made with wheat seedlings in good Leonardtown loam and poor Leonardtown loam from St. Mary County, Md. The good soil under field conditions gave about 20 bushels of wheat and the poor soil about 5 to 8 bushels, under the

cultural methods to which they had been subjected in recent years. Two baskets were filled with each of these soils containing the optimum water content, and six wheat seedlings were planted in each on November 13.

The six plants grown on the good Leonardtown loam weighed 0.63 gram, and on the poor Leonardtown loam 0.41 gram. The superficial volume of the soil, taking an average of the two baskets in each case, was 303.05 cc. and 312.82 cc. The dry soil weighed 441.28 grams in the one case, and 465.42 grams in the other. The weight of water was 87.42 grams, or 19.84 per cent, in the good Leonardtown loam, and 91.89 grams, or 19.64 per cent, in the poor Leonardtown loam, while the volume of air space was 49.12 cc., or 16.09 per cent, in the first case, and 45.33 cc., or 14.49 per cent, in the second case. The total amount of transpiration during 28 days was 206.95 grams from the good Leonardtown loam, and 185.65 grams from the poor Leonardtown loam. The soil was apparently more compact than in the case of the Cecil clay, and was not in so loamy a condition. The volume and percentage of air space was also smaller, but the moisture conditions seemed very uniform and satisfactory at the end of the experiment, and the distribution of the roots in the soil was uniform. About the same difference was noted in the condition of the roots, as already described under Cecil clay.

Experiments of the same kind were made with eighteen wheat seedlings in the very infertile lawn from Takoma Park, and with the same number of seedlings in the much more fertile sod from Takoma Park, three baskets being used in each case, with six plants in each. The seedlings were planted on November 4.

At the termination of the experiment six plants grown on the lawn soil weighed 0.45 grams and from the sod 1 gram. The superficial volume of the soil was 313.78 cc. in the lawn and 317.22 cc. in the sod. The dry soil weighed 467.33 grams in the one case and 416.31 grams in the other. The water present was 54.31 grams, or 11.61 per cent, in the lawn and 57.91 grams, or 12.97 per cent, in the sod. The volume of air space was 83.14 cc., or 26.51 per cent, in the former, and 105.56 grams, or 33.40 per cent, in the latter. The total amount of water transpired by the eighteen plants grown on the lawn soil was 523.55 grams against 668 grams from the sod. The conditions of moisture at the termination of the experiment were very uniform. The roots had developed well through the soil, but there was the same difference of growth, as was shown in the experiments already described.

Another series of experiments was begun with the same lawn soil at Takoma Park and with soil from a flower bed prepared in the lawn by a very heavy application of well-rotted stable manure. The manure was thoroughly incorporated with the soil, the bed having been spaded up several times during a period of three months previous to the begin-

ning of the experiment. A sample of the sod soil was also carried in this experiment for the purpose of comparison. Two baskets of each soil, with six wheat plants in each basket, were used in this experiment.

At the termination of the experiment it was found that the plants grown upon the sample from the bed weighed 0.76 gram, from the sod 0.67 gram, and from the lawn 0.35 gram. The superficial volume of the soil in each case was 301.22 cc., 282.25 cc., and 286.50 cc., respectively. The dry soil weighed 365.99 grams, 408.45 grams, and 351.27 grams. The weight of water was 57.85 grams, or 15.70 per cent, for the bed, 69.05 grams, or 16.90 per cent, for the sod, and 37.70 grams, or 10.58 per cent for the lawn. The volume of air space was 105.26 cc., or 35.06 per cent, 59.08 cc., or 20.96 per cent, and 135.10 cc., or 47.21 per cent, respectively. The difference in the water content represents the difference in the optimum amounts required for these different soils. The weight of water transpired during the period of twenty-eight days was 217.05 grams for the soil from the bed, 192.45 grams for the sod, and 159.35 grams for the lawn.

Samples of the very intractable and unproductive Susquehanna clay and of the equally unproductive white clay from the Soldiers' Home were used in another experiment, two baskets being taken of each with six wheat seedlings in each basket. These were compared with good Cecil clay seeded at the same time.

At the end of the experiment the six plants from the Susquehanna clay weighed 0.24 gram and from the Soldiers' Home 0.32 gram. The superficial volume of soil in each pot of the Susquehanna clay was 283.83 cc. and of the Soldiers' Home 289.98 cc. The weight of the dry soil was 349.59 grams and 364.86 grams, respectively. The weight of water was 93.42 grams, or 26.73 per cent, in the Susquehanna clay, and 87.50 grams, or 23.78 per cent, in the Soldiers' Home. The air space was 58.50 cc., or 20.59 per cent, in the former, and 63.66 cc., or 21.91 per cent, in the latter. The amount of water, although high, represents the optimum quantities for these two soils. The total amount of transpiration during the fourteen days was 43.30 grams for the Susquehanna clay and 41.15 grams for the white clay from the Soldiers' Home, as against 82.50 grams for the good Cecil clay. The condition of the soil at the end of the experiment, as is usual with this material, was found to be so plastic that it was difficult to remove it from the pot. It was close and tenacious and altogether an unfavorable medium for plant growth. The water, however, was evenly distributed, and the volume and percentage of air space, although small, was larger than in the case of the Leonardtown soils. The roots were very poorly distributed and the plants were very small, indicating a strong probability that the plants would not long have survived, or, if



they had, would have made but a poor and stunted growth. In another experiment with the Susquehanna clay, in which great pains had been taken to get the material into a granular structure, the plants had developed well, the roots had apparently grown well into the large interstitial spaces between the soil granules, and the transpiration was practically the same as from plants grown upon good Cecil clay, indicating, as has been already suggested, that the fault of this soil is mainly mechanical, and that under certain physical conditions, where an abundance of air is provided and relatively large spaces are left in the soil through which the roots can develop, satisfactory results can be obtained even with this soil. Although this soil under ordinary cultural methods gives a very low yield, it nevertheless unquestionably possesses a degree of fertility which makes it comparable with the Cecil clay, or possibly with the Hagerstown loam, with which it has so often been contrasted.

#### EXPERIMENTS WITH ARTIFICIAL CULTURE SOLUTIONS.

The following experiment was undertaken to determine if the nature of the combination of the different bases and acids entering into the solution exerted an appreciable influence upon the development and transpiration of the plant. From chemically pure salts containing the bases calcium, magnesium, potassium, sodium, and ammonium, and the acids sulphuric, hydrochloric, nitric, carbonic, and phosphoric, a set of twenty solutions was prepared, each containing all the bases and acids, but in every case combined in different ways. In order to have the solutions of as uniform a concentration as possible the base calcium was in each case taken as a standard and a solution made up to a strength equivalent to ten parts per million of this constituent, the other constituents being present in equivalent combining proportions. The results of this experiment are inconclusive, in that the differences were not greater than would be expected from experimental errors, and from the limited number of solutions investigated it was not possible to associate such differences as did come out with any one constituent or combination of constituents. To settle this point finally a much larger number of solutions and a very much larger number of plants must be taken, and this work will probably be pushed to a conclusion. Sufficient was developed, however, to indicate that there was no material difference due to the forms of combinations used.

Other experiments have indicated that the concentration of the soil extract made in the conventional way already described had little noticeable effect on the development of plants when the extract was diluted as much as ten times. To test this point more thoroughly a nutrient solution was prepared with a concentration of 100 parts per million with respect to calcium, the other constituents being present

in chemically equivalent proportion, excepting the iron, which was present only in a trace. Portions of this solution were diluted in such a way as to contain 50, 10, 5, and 1 part of calcium per million. Five series of experiments were carried on with these solutions at different seasons of the year under different climatic conditions and using a large number of plants. The results obtained from these five series of solutions indicate a maximum transpiration from the solution containing about 10 parts per million of calcium or a total salt content of about 170 parts per million. In other words, this is the concentration of a nutrient solution, with the conditions under which these experiments were carried on, which was found to give the most satisfactory results, but it is worthy of note that the actual differences between the transpiration in solutions containing 10 parts of calcium and equivalent parts of the other constituents, and one containing 1 part or 100 parts of calcium, the other constituents in equivalent proportion, was quite small.

Further experiments were then made by increasing the concentration of the solution containing 1 part per million of calcium with the addition of one salt at a time, such as sodium chloride or potassium sulphate, etc., making the solution equivalent to one containing 10 parts per million of calcium. In all cases it was found that a concentration of about 170 parts per million of total dissolved salts was the most desirable, provided that at least 1 part per million of each constituent was present.

#### EXPERIMENT WITH STERILIZED MEDIA.

Having experimented with the lawn soil by growing plants in soil extracts, by growing them in pots, and also by growing them in small plats upon the lawn itself, with the addition of the usual assortment of plant foods and plant food constituents, attaining inconclusive and unsatisfactory results, it was decided to take up the work from a different direction. Some of the lawn extract contained in glass flasks protected with a wad of cotton was heated on two successive days for about half an hour in such a manner that the solution simmered, but did not actually boil. Transpiration from plants grown in this sterilized extract was considerably greater than from an equal number of plants grown in the untreated extract.

A lawn extract evaporated to dryness, charred and taken up with an amount of water equal to that originally present, gave much higher transpiration than from the untreated extract.

Some of the extract from the lawn filtered through fine purified charcoal gave much higher transpiration than from the untreated soil extract. Determinations with potassium permanganate indicate that the treatment with charcoal had removed all appreciable organic matter from the solution.

Lawn extract treated with permanganate of potash to destroy organic matter, and then treated with charcoal to remove the excess of permanganate and filtered, gave higher transpiration than the untreated extract.

Some of the lawn soil was treated for several days with fuming nitric acid over a steam bath to remove the organic matter. The soil thus treated was heated to drive off the nitric acid, then washed as in making an ordinary soil extract, and the soil was planted in pots, and gave a much higher transpiration and better plants than the original soil.

Some of the lawn soil, charred until it turned quite black and then used in wire baskets directly after charring, gave a lower transpiration than the untreated soil. This was accompanied by a very rapid growth of mold and fungus in the charred soil which finally killed the plants.<sup>a</sup> When the charred soil was exposed to weathering influences for some time before planting, the plants gave a higher transpiration than in the untreated soil, and no tendency was manifested for the development of molds, fungi, etc. The weathering of the charred soil seems to be accompanied by a loss of soluble organic matter.

Extracts from the charred lawn soil also showed this tendency to mold, and the transpiration results were inconclusive.

Some of the lawn soil was then successively extracted in the usual way with water. The plants were grown in these extracts and between each extraction the soil was dried at 100° C. Plants grown in each successive extraction showed a higher transpiration at first, but the tendency to mold became very much greater and more pronounced, and the amount of soluble organic matter as determined by the permanganate method increased very much with each successive extraction of the soil.

#### STUDY OF ORGANIC MATTER IN THE LAWN SOIL.

The lawn at Takoma Park, D. C., upon which many of these experiments were made, is naturally a very poor, rather sandy soil. It is yellow or gray in color with the exception of a slight layer of darker material at the immediate surface. Determinations in the yellow portion of the soil show about 3 per cent of organic matter, although the general appearance of the soil would not suggest a content of over 0.5 per cent. Attempts have been made to improve this lawn by applications of manure. It was noticed that the manure quickly

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<sup>a</sup>In this connection it is interesting to note the observations of Browne (*Science* 20, 179, 1904) "that cane juice and plant tissues generally are much less readily attacked by molds and ferments if they have not been previously sterilized, owing probably to the formation of protective toxines, which Bertrand has suggested to be an inherent property of all freshly exposed plant tissue. And further, this protective action is usually accompanied by a blackening or darkening of the tissue."



disappeared and did not have the effect on the soil that was desired. There was no marked change in color even after two applications of 25 tons of manure per acre. Experiments indicate that organic matter added to the lawn oxidizes directly, the amount of carbon dioxide given off being equivalent to the amount of oxygen absorbed by the soil in closed vessels. The organic matter added to the lawn in its present condition decomposes very quickly, with little if any formation of humus. In this respect the lawn, which is a very dry-natured soil, seems to act similarly to a dry earth closet.

Humus prepared from a number of soils appears inert when added to a culture solution in the proportion of from 1 to 100 parts per million, neither increasing nor diminishing transpiration of the plants. Practical experience and our own experiments indicate that if the organic matter of the lawn can be converted into humus the conditions under which this takes place will be those under which the lawn would be fertile.

In its present form the organic matter of the lawn seems to be a medium for molds and ferments. A soil already containing much humus is presumably one in which organic matter is readily and quickly converted into humus and in which there will be a small amount of active organic decomposition products. In this connection it may be stated that when lime, charcoal, ferric hydrate, or a similar substance is added to a nutrient solution we get a higher transpiration, a larger leaf development, and a very much larger and healthier root development, with less tendency to mold and without the accumulation of organic matter in the solution normally given off by the roots of plants.

Application to the lawn of substances which would destroy molds and ferments and not at the same time injure the seedling plants gave inconclusive results. The application of certain green plant tissues, finely ground and mixed with the soil, were found to act differently from the manure which had been used. Finely ground fresh sumac leaves mixed in various proportions up to 1 per cent of the weight of the soil, when the soil was maintained at its optimum water content and frequently stirred, caused the soil to darken with the apparent formation of humus. The color change that naturally takes place in leaves under these conditions seemed to take place in the organic matter of the soil also, the extent of the effect being proportional to the amount of leaf used, between the limits 0.1 per cent and 1 per cent, beyond which heavier applications turned the soil quite black. Hickory leaves tried in the same way had a somewhat different effect, as after the action had continued for some time the small particles of leaf appeared quite black, but the adjacent soil grains were but little affected. Oak leaves appeared to cause a greater effect in the organic matter of the soil than did the hickory, but not so much as did the sumac; and finely

ground green clover appeared to cause about the same effect as did the oak leaf. The aqueous extract from macerated sumac leaves passed through a Pasteur-Chamberland filter produce the same effect upon the soil as the ground leaf itself.

The physical characteristics of the soil seemed to have been materially changed by these applications, especially with the sumac, the soil, which was originally light yellow in color and sandy in texture, acquiring a rich brown color and a loamy texture such as is usually associated with good condition and a fertile soil.

These changes in color and other physical properties of the soil take place with great rapidity, especially upon the surface exposed to the air, and if the mass be frequently stirred, especially with free exposure to sun and air, the change seems to be complete, at least in samples of a few kilos weight, within a few hours, or at most within a day or two.

Pyrogallol appeared to produce the same effect upon the soil as did the fresh sumac leaves, causing it quickly to acquire a rich brown color, and if considerable amounts of this phenol were used, almost a black color. The corresponding percentages of the pyrogallol and the fresh sumac leaf necessary to produce the same intensity of color in the soil appeared to be about in the ratio of 1 to 10. In all cases after the application of these substances to the soil there is a considerable amount of soluble organic matter present.

Ordinary fertilizer substance like sodium nitrate, kainite, potassium sulphate, potassium chloride, and lime appear to have a similar influence, in that they darken the soil, although not to the extent as do the pyrogallol or sumac leaves.

The soil, after treatment with the green substances or pyrogallol as described above, when planted to wheat seedlings, causes a higher transpiration than the untreated soil. The sanitary conditions in the soil appear to be improved by these oxidizing agents. The increase in transpiration and in the development of seedling plants produced by such treatment is far more pronounced than by any other method tried, and approaches the most perfect condition of sand culture.

Similar results are indicated for the poor Leonardtown loam at Leonardtown, Md., and for the poor Cecil clay at Statesville, N. C., where similar work is being conducted.





